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ADAPTING THE EXPERIENCE CURVE FOR ESTIMATING BIOREFINERY COSTS

SEYEDEHSAHAR MOHAMMADI

DÉPARTEMENT DE GÉNIE CHIMIQUE

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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Ce mémoire intitulé:

ADAPTING THE EXPERIENCE CURVE FOR ESTIMATING BIOREFINERY COSTS

présenté par : MOHAMMADI SEYEDEHSAHAR

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a été dûment accepté par le jury d'examen constitué de:

M. TAVARES Jason-Robert, Ph.D., président

M. STUART Paul, Ph.D., membre et directeur de recherche

M. BENALI Marzouk, Ph.D., membre

DEDICATION

To my family

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RÉSUMÉ

Le secteur des pâtes et papiers du Canada est aux prises avec des difficultés financières en raison de la diminution de la demande pour les produits papetiers traditionnels, la concurrence accrue provenant des pays à moindre coût de main-d'œuvre et de matières premières, et l'augmentation des prix de l'énergie. L'intégration de bioraffineries dans ce secteur permettrait de diversifier le portefeuille de produits et les sources de revenus, et améliorer la compétitivité de l'industrie. Cependant l'intégration du bioraffinage soulève des incertitudes quant aux coûts de production. Une mauvaise estimation des coûts du bioraffinage à différents stades de développement (laboratoire, pilote ou démonstration) peut affecter la qualité des décisions prises au sujet de la commercialisation. Toute compagnie papetière a besoin d'évaluer avec précision les coûts de production des candidats au bioraffinage, qui varieront au cours du temps, afin de prendre des décisions éclairées pour l'avenir.

L'objectif de cette thèse est de proposer un modèle d'évaluation des coûts des nouvelles technologies de bioraffinage avant et après la commercialisation en s'inspirant de l'approche basée sur la courbe d'expérience, et de l'appliquer ensuite à des études de cas basés sur un procédé de séparation et production de lignine intégré dans une usine de mise en pâte Kraft.

La méthodologie utilisée dans cette thèse inclut une revue de la littérature sur les méthodes d'estimation des coûts, sur les courbes d'expérience pour les technologies dans le domaine de l'énergie et sur le bioraffinage forestier, la proposition et l'adaptation d'un modèle d'évaluation de coûts de bioraffinage, l'application de ce modèle à des études de cas de bioraffinage basé sur la valorisation de la lignine. L'application à des études de cas inclut une analyse par large blocs (LBA), l'évaluation des facteurs de sous-estimation et de réduction des coûts, et leur utilisation dans le modèle basé sur les courbes d'expérience.

Les facteurs fondamentaux qui influent sur les coûts avant et après la commercialisation des produits de bioraffinage ont été identifiés. Les facteurs influençant le coût de production lors de la mise à l'échelle commerciale sont les suivants: le caractère novateur de la technologie; le niveau de l'ingénierie de conception; l'appréciation du risque associé à l'intégration ; le biais d'optimisme des développeurs de technologies et de projets. Les facteurs influençant le coût de production après la mise à l'échelle commerciale sont les suivants: les économies d'échelle ;

l'amélioration des procédés en raison de l'apprentissage; le moindre conservatisme dans la conception en raison de l'apprentissage ; l'amélioration incrémentielle des procédés résultant de ajout de nouvelles technologies. Un modèle basé sur ces facteurs a été proposé ; il a été ensuite appliqué à des études de cas.

Deux études de cas de bioraffinage basé sur la lignine ont été identifiées et sélectionnées selon leur technologie novatrice et leur différent niveau de développement : un procédé de séparation et valorisation des principaux constituants de la biomasse forestière qui utilise un solvant organique (solvent pulping); et un procédé de précipitation et extraction de la lignine contenue dans la liqueur noire du procédé de pâte kraft, suivi d'un traitement produisant un précurseur de résine phénol-formol. Pour la première mise à l'échelle commerciale, les deux études de cas ont montré une sous-estimation des coûts. Les coûts du procédé basé sur un solvant organique doivent être réévalués de 200 dollars par tonne de résine phénol-formol, tandis que ceux du procédé de précipitation et traitement de lignine doivent être réévalués de 100 dollars par tonne de résine phénol-formol. Pour la situation après la production à l'échelle commerciale, les coûts de production doivent être réduits dans les deux études de cas. Les coûts de production relatifs aux procédé basé sur un solvant organique diminuent de 23% quand la production cumulée double (ratio d'amélioration = 0.77); Les coûts de production relatifs au procédé de précipitation et traitement de la lignine diminuent de 4% quand la production cumulée double (ratio d'amélioration = 0.96).

L'application de ce modèle peut apporter des informations essentielles sur les coûts des technologies de bioraffinage et être utilisée pour les processus de prise de décision tels que la prise de décision multicritères (MCDM). Par exemple, sur la base des résultats obtenus, on peut comprendre que le procédé de précipitation et traitement de la lignine produisant le précurseur de la résine phénol-formol est plus prometteur à court terme car les coûts d'investissement et d'opération sont inférieurs. Cependant, le procédé basé sur le solvant organique offre plus de possibilités de réduction des coûts de production à l'échelle commerciale et permet de produire de la lignine de meilleure qualité et en quantité supérieure.

Les futurs travaux pourraient inclure l'application de ce modèle à d'autres études de cas afin d'affiner notre compréhension des différences entre les coûts réels et estimées, et sa validation.

Des informations fournies par le modèle pourraient être utilisés dans des processus de prise de décision tels que la technique de décision multicritère (MCDM).

ABSTRACT

Canadian Pulp and Paper (P&P) sector is struggling with financial difficulties. This is due to decreases in demand for their traditional products, increasing energy prices and increased competition from low-cost countries. Biorefinery integration into this sector can bring competetiveness by diversifiying products portfolio and revenue sources.

There are some uncertainties in integration of emerging biorefineries into P&P sector, such as first implementation costs and long-term competitiveness. On the other hand stage of development (laboratory, pilot or demonstration scales) of a biorefinery affects level of these uncertainties. This in turn makes comparison of biorefineries options more challenging. Poor cost estimation of biorefineries affect the quality of decision made about commercialization. Moreover In order for a pulp mill to make well-informed decisions, it is necessary to forecast commercial costs.

The objective of this thesis is to propose a model inspired by experience curve approach to evaluate costs of emerging biorefinery technologies before and after commercialization. The model is applied in lignin-based case studies considering retrofit biorefinery implementation into a Kraft P&P mill.

The methodology to accomplish the objective of this thesis consists of:

- Reviewing literatures on
    - Early cost estimate analysis
    - Experience curves of energy technologies
    - Forest biorefineries
- Proposing a model to underline factors impacting costs before and after commercialization
- Application of model into two retrofit lignin-based biorefinery case studies:
    - Large Block Analysis (LBA) on the case studies
    - Evaluating the identified factors before and after commercialization
    - Operating the experience curve model based on gathered data from previous steps

Fundamental factors that affect costs before and after commercialization of emerging biorefineries are identified. Then a new of experience curve based on these factors is proposed. The factors affecting the first commercial cost are:

1- New technology
2- Appreciation for and level of design engineering
3- Appreciation for risk associated with integration and scale up
4- Optimism bias of the technology and project developers.

The factors affecting the post commercial costs are:

1- Economies-of-scale
2- Process operation optimization due to learning
3- Process design optimization and less conservatism in design due to learning
4- Process improvement with new technology additions post-implementation.

The two lignin-based biorefinery case studies for application of this model were; solvent pulping and lignin precipitation processes. For the first commercial scale, both case studies showed cost underestimation; solvent pulping process by 200 ($ per ton of PF resin precursor) and lignin precipitation by 100 ($ per ton of PF resin precursor).

At post commercial scales, costs of both case studies were reduced; solvent pulping with progress ratio of 77% and lignin precipitation with progress ratio of 96%.

Application of this model can bring critical information about costs of biorefinery technologies in pre and post commercial scales for decision-making processes such as Multi Criteria Decision Making (MCDM). Fore example based on the achieved results, it can be understood that in short term of business strategy lignin precipitation process with less cost per ton of lignin precursor is more promising. On the other hand in long-term business strategy when demand and market of lignin products such as PF resin precursor are developed, solvent pulping process is more beneficial. This is mainly due to three factors:

- More opportunities for cost reduction at commercial scales
- More quantity

- Better quality of lignin

Future work includes application of this model to more case studies to enhance its understanding. Furthermore suitable criteria based on achieved information from this model should be defined for decision-makings techniques. This will help to validate further the importance of this provided information.

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AFEX	Ammonia Fibers Expansion
AHP	Analytic Hierarchy Process
CBP	Consolidated Bio- Processing
CHP	Combined Heat and Power
IPA	Independent Project Analysis
LBA	Large Block Analysis
MAUT	Multi-Attribute Utility Theory
MADM	Multi-Attribute Decision-Making
MCDM	Multi-Criteria Decision Making
M&E	Mass and Energy
MODM	Multi-Objective Decision Making
MOO	Multi-Objective Optimization
MT	Million Ton

NEEDS	Energy Externalities Developments for Sustainability
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
P&P	Pulp and Paper
PF-resin	Phenol-Formaldehyde resin
PFF	Primary Forest Fuel
PR	Progress Ratio
SCS	Southern Company Services
SHF	Separated Hydrolysis and Fermentation
SSCF	Simultaneous Scarification and Co-Fermentation
SSF	Simultaneous Scarification and Fermentation
t	Ton

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CHAPTER 1: INTRODUCTION

1.1 Problem statement

Recently forest product industry, specifically P&P mills are facing different financial challenges. This is due to decreasing demand of their traditional products, increasing price of energy and growing competition from countries with less price of energy and labor. In order to survive in this situation business transformation is critical. This could be provided by biorefinery integration. Biorefinery is referred to any technologies, which uses same incoming biomass and other raw materials, including energy, as their feedstock for simultaneous production of paper fibers, chemicals and energy. This technology helps to diversify business of P&P industry and to bring competitiveness by producing new products including added value and commodity products.

However implementation of biorefinery technologies same as other new technologies has buriers and uncertainties [1]. In case of their technology's cost there are three challenges:

- Biorefinery technologies are at different stage of development (laboratory, pilot or demonstration scales). This makes their comparison challenging for pulp mills.
- There are uncertainties and misestimating in early design cost estimation of first commercial scale. This is mainly due to new technologies and lack of project definition. Misestimating of biorefinery costs decrease the quality of decision and planning for commercialization.
- Lack of cost data at commercial scales of emerging biorefineries to predict post commercial cost trends and to compare their competitiveness. Commercial costs information is necessary for forestry companies to make better decisions on candidate technologies. This is based on a comparison of their costs not only for first commercial scale but also for post commercial years.

So the contribution in this M.Sc. project is to address these challenges by proposing a model of experience curve uniquely for emerging biorefineries. The biorefiney experience curve model analyzes cost estimation of first commercial scale, predicts future cost trends and brings dissimilar biorefineries with different stage of development to a same basis for further comparison. This model address main factors of cost misestimating in pre-commercial scale and factors of cost reduction in commercial scale. The main found factors for pre-commercial scale are: new technology, appreciation for and level of design engineering, etc. The main identified factors for post-commercial are: economies-of-scale, 2- process operation optimization due to learning, etc. Later the information from biorefinery experience curve approach can be used in the decision-making of biorefinery case studies for integration into a P&P mill.

1.2 Objectives

According to the problem statement of this work by title of "adapting the experience curve for estimating biorefinery costs" following hypothesis are provided:

- A systematic model, employing concept of experience curve can be adapted in a practical manner for the case of biorefineries implemented in retrofit in P&P industries for the comparison of future capital and operating costs.
- Knowledge of the evolution of biorefinery technology capital and operating costs over time is critical for decision making during the early design stage when establishing biorefinery strategy.

Then the main objectives are defined as following:

- To propose and demonstrate a systematic cost analysis model for the integrated forest biorefinery strategies inspired by experience curve.
- To apply the systematic methodology in lignin based biorefinery case studies, and make information from application of this tool available for decision-making.

1.3 Thesis organization

This thesis includes following sections:

- Chapter 2. Reviewing of relevant literatures to find the gaps in the body of knowledge.
- Chapter 3. Presenting the methodology to achieve objectives of this study
- Chapter 4. Synthesizing the results of developing the experience curve model and

applying for the case studies.

- Chapter 5. Presenting the general conclusions.
- Chapter 6. Presenting the contributions to the body of knowledge and recommendations for future works.

CHAPTER 2: LITRATURE REVIEW

2.1 Forest biorefineries

In this study the effort is to adapt the experience curve for the emerging biorefinery technologies such as forestry biorefineries that are mostly at pre-commercial scale.

2.1.1 Definition

There is no common definition for forest biorefinery. In definition of Taskforce [2], the forest biorefinery is the effective use of the all potential raw materials of forest industry to produce a wide range of added value products. In a definition of National Renewable Energy Laboratory (NREL) [3] a biorefinery is integration of equipment and conversion processes to generate fuels, power and chemicals from biomass. Figure 2-1 shows two platforms of NREL's biorefineries: sugar platforms and syngas platform. The "sugar platform" focuses on fermentation of sugars that is extracted from biomass by biochemical conversion processes. The "syngas platform" focuses on the gasification of biomass by thermochemical conversion processes.

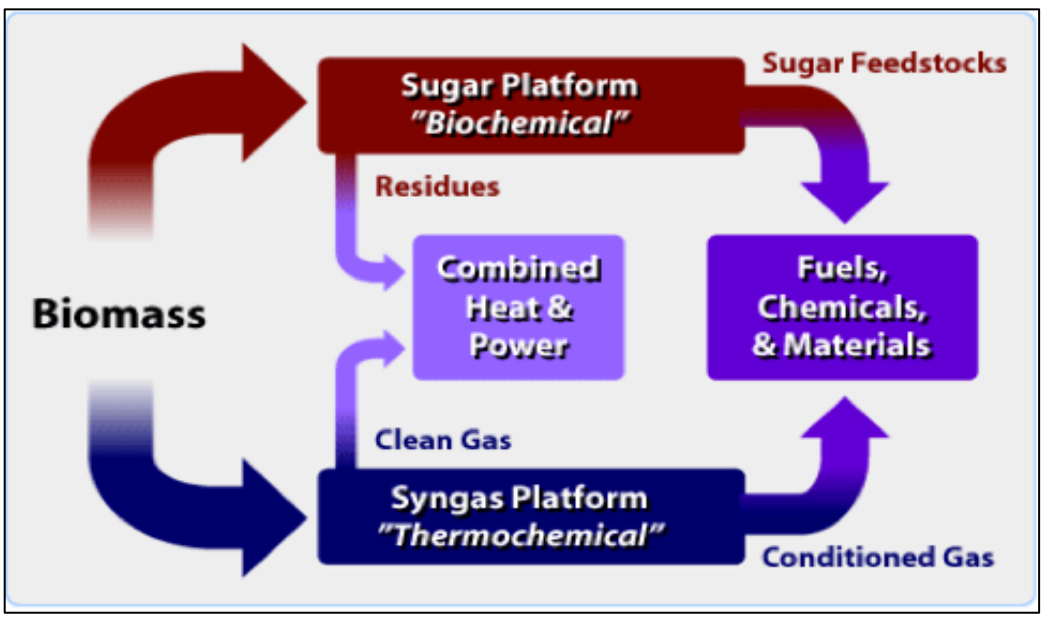


Figure 2. 1: Forest Biorefinery concept [3]

Forest Biorefinery can diversify product portfolio of forest industry. This task can be done by using all components of biomass and transforming them into commodity and/or value added products. It can produce chemicals, polymers, products for pharmaceutical industry, green energy, liquid fuels and hydrogen etc. [3].

There is a strong similarity between the forest biorefinery and petroleum refinery. In an oil refinery, different types of fuels and chemicals are produced from oil. In biorefinery, different types of biomass are used to produce different chemicals, different fuels and green energy.

2.1.2 Classification of forest biorefinery concept

The biorefinery processes are classified based on a various criteria. This could be based on types of conversion process and final product. Based on types of conversion processes, there are three main categories:

- Chemical (e.g. lignin precipitation) [4]
- Biochemical (e.g. hemicellulose extraction and fermentation)
- Thermo-chemical (e.g. biomass gasification, and rapid pyrolysis)

Biorefinery products are divided in two groups:

- Energy products (e.g. bioethanol, biodiesel, and synthetic biofuels)
- Material products (e.g. chemicals, materials, food and feed) [5].

2.1.2.1 The chemical conversion process

The chemical way includes lignin precipitation technologies and processing of lignin to value added products. Lignin can be obtained from spent pulping liquors of pulping processes or biomass fractionation methods for the production of many chemicals and biomaterials [6], [7]. Physicochemical properties of lignin depend on the quality of the biomass, and the methods that is used for biomass conversion and lignin separation. From one type of lignin to another the average molecular weight, chain lengths distribution, the amount of reactive groups, the solubility in water and other physicochemical properties may differ significantly. This variations in the properties of lignin must be taken in to account in the choice of products that will be produced from lignin [8].

2.1.2.2 The biochemical conversion process

The biochemical pathway produces value-added products by combining pretreatment technologies, hydrolysis technologies and fermentation processes.

Biomass pretreatment

In pretreatment step the goals are to destroy the lignin that is surrounding the cellulose fibers. This is to reduce the crystallite of cellulose in order to increase its porosity to be more accessible for the subsequent hydrolysis step. Pretreatments are classified in three groups: physical, chemical or biological. Quality of pretreatment affects yields of hydrolysis step to produce mono-sugars. Therefore these technologies are chosen based on types of feedstock. For example for corn Stover it has been found that the Ammonia Fibers Expansion (AFEX) and for poplar wood, calcium oxide or sulfur dioxide based pretreatments are more effective [9], [10].

Hydrolysis

Hydrolysis or saccharification is a step in which carbohydrates are broken into their sugar molecules components. For example sucrose is broken down into glucose and fructose. Generally, hydrolysis makes oligomers of carbohydrate sugars ready for fermentation process. There are two types of hydrolysis techniques; acidic and enzymatic. Acidic hydrolysis can be performed by a dilute acid or by a concentrated acid. In case of dilute acid high operating temperatures of the product and organic acids are required. In concentrated acid hydrolysis large amounts of acid are required. This in turn makes this method uneconomic especially when the acid is not recycled effectively. In enzymatic hydrolysis, cellulase enzymes are used and inhibitors are not generated, so it is considered to be the most promising process [11].

Fermentation

Mono sugars from hydrolysis steps are brought to fermentation step to produce alcohol. There are various techniques for fermentation of sugars.

- Separated Hydrolysis and Fermentation (SHF): hydrolysis and fermentation steps are performed separately, which increase flexibility of this process.
- Simultaneous Scarification and Fermentation (SSF): In this configuration hydrolysis and fermentation are combined in the same processing step. SSF is considered to be very effective for the production of a specific product such as ethanol.

- Simultaneous Scarification and Co-Fermentation (SSCF): the hydrolysis and fermentation of C_5 and C_6 sugars are carried out simultaneously.
- Consolidated Bio- Processing (CBP): this method combines, the cellulose production steps, hydrolysis and fermentation of C_5 and C_6 sugars in the same processing step [12].

2.1.2.2 The thermo-chemical conversion process

In this technique thermal conversion methods are carried out to produce bio-oil or synthesis gas from biomass. Two main thermochemical techniques are: direct liquefaction (pyrolysis) and indirect liquefaction (gasification).

Pyrolysis

Pyrolysis is the thermal treatment of biomass at elevated temperatures and in the absence of oxygen to produce black liquid called bio-oil. The fast pyrolysis, compared to other techniques of pyrolysis, has the highest yield of bio-oil production.

Gasification

Gasification technique is used to produce synthesis gases from biomass. There are various gasification techniques: the air blown or oxygen blown, direct heating or indirect heating. Then the produced synthesis gas is cleaned and chemically or biologically transformed to different products [13].

2.1.3 Forest biorefinery integration to P&P mills

2.1.3.1 Transformation of forestry sectors

Biorefinery technologies can diversify products portfolio of P&P industry. These technologies were studied for P&P mills transformation using different strategies [14]–[16].

One strategy is to use pulp mill's waste liquor stream [2]or a stream prior to pulping process (creation of Value Prior to Pulping (VPP)) [17]–[20] as raw material. In VPP technique some hemicelluloses are separated prior to cooking wood chips to produce value added products. These waste liquors are mainly used for black liquor gasification or technologies of lignin separation.

Another strategy of biorefinery integration is to implement it in parallel to pulping process. This method use different types of biomass to produce different types of products by separated processing lines from existing pulp lines. Integration brings a lot of advantages for P&P sector mainly. This is due to energy integration, the use of centralized utilities, supply chain integration and sharing overhead manufacturing. In this perspective of biorefinery implementation, Hytönen et al. [21] carried out a systematic assessment of bioethanol processes integration into a Kraft pulp mill. The biorefinery case studies of this work use conventional or emerging raw materials such as forest residues, corn stover or residues from food industries. According to the authors, the biorefinery integration resulted in new revenues from production of new bio-products. Moreover it resulted in reduction of production costs of pulp.

2.1.3.2 Biorefinery technologies integration to the P&P industry

Several biorefinery technologies are designed specifically for P&P industry. These technologies are implemented in retrofit installation to improve revenue creation of existing operations process. Wising et al. [16] carries out a review of the most developed biorefinery technologies. This review includes: lignin separation, hemicellulose extraction and black liquor gasification processes.

There are three main methods of lignin separation:

- Ultrafiltration,
- Electrolysis
- Acid precipitation

Among these methods acid precipitation using CO_2 as acidifying agent is the most promising technology [22], [23].

Hemicellulose extraction before pulping process is used to produce bioethanol or other products. This can be a great opportunity for P&P industry. This process can be done by several techniques such as:

- Hemicellulose extraction in neutral environment (a fraction of about 10% by weight of dry wood can be extracted) [18]
- Hemicellulose extraction by dilute acid pre- hydrolysis (by extraction rate of 6 to 18% of dry wood) [19]
- Hemicellulose extraction by hot water [1]
- Hemicellulose extraction using basic solution containing NaOH (extracting 40-50 kg hemicelluloses per ton of wood chips) [17]

Moreover hemicellulose extraction before pulping relieves the pulp process and increases the rate of pulp production [18].

Gasification produces a syngas produced from black liquor. This can be done by converting its biomass content into gaseous energy carrier. The syngas is used as a source to generate electricity or to synthesize biofuels or green chemicals. There are two types of gasification: low temperature/solid phase and high temperature/smelt phase [24].

2.1.3.3 Stages of the biorefinery implementation in the P&P industry

A strategic approach to implement forest biorefinery in P&P mills is shown in figure 2-2 [25].

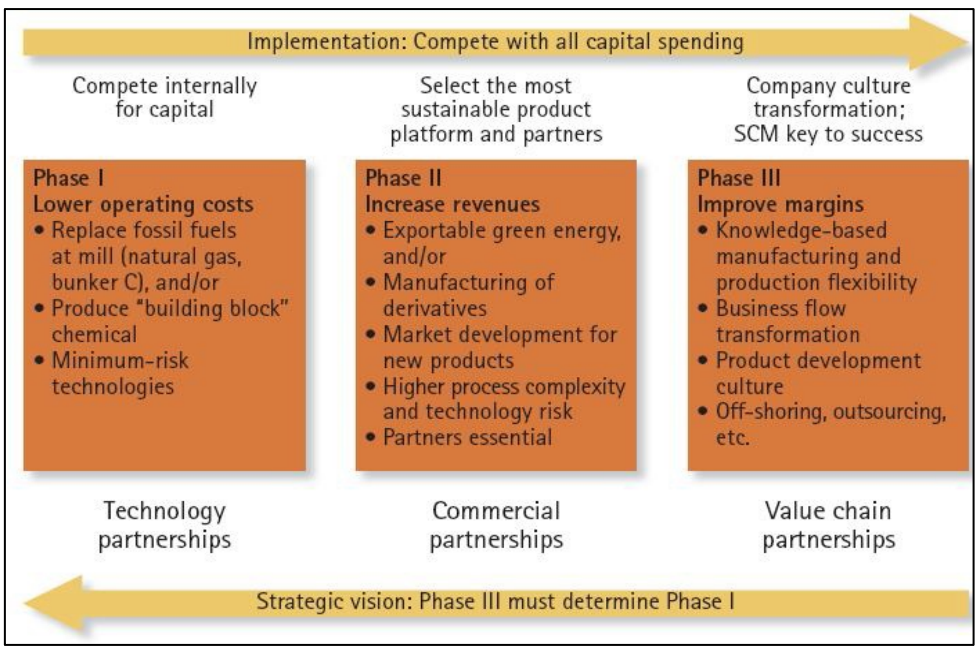


Figure 2. 2: Integrated biorefinery implementation by phased approach [25]

There are three progressive stages in this approach: Phase I, II and III.

- Phase I: At this phase objective of biorefinery integration is to reduce the operating costs of P&P mills. This can be achieved by using e.g. biomass fuels instead of fossil fuels. Therefore in this phase there is no market risk. The reason is that the biorefinery's products will be consumed at the plant.
- Phase II: The main objective of this phase is to produce new value-added products by implementation of a biorefinery strategy. This in turn can bring new revenues. In this phase of biorefinery implementation, there are some risks related to the process complexity and supply chain. This is important to be taken in to account to minimize market risks and increase profitability. In order to overcome financial difficulties of this phase, it is suggested to have partnership with partners outside the forest sector.
- Phase III: At this phase the objective is to increase margins and beneficiaries. This can be done by optimizing the supply chain and increasing process flexibility.

These three phases have to be defined by forestry companies before embarking on Phase I. This in turn helps to ensure the success of P&P mill transformation.

2.1.4 Lignin based biorefineries

Lignin precipitation processes precipitates lignin from black liquor of Kraft pulps. This lignin due to its high heating value can be used as a carbon neutral replacement for fossil. Alternatively in a solvent process high-purity lignin can be produced and transformed into other added-value products. Lignin is an abundant, renewable and amorphous natural polymer. It consists of phenyl propane units (Syringol, Guaiacol, and P-hydroxyphenol). These units are linked together by ether and carbon-carbon inter-unit bonds. Lignin can be used for the production of various chemicals and value added products such as carbon fiber, activated carbon, phenols, etc. Three categories of lignin products are:

- Fuel and electricity
- Macromolecules
- Aromatics and miscellaneous monomers.

Macromolecules category includes products such as carbon fiber, polymer modifiers, adhesives and resins. Aromatic category includes products such as chemicals derived from BTX (benzene, toluene, and xylene), phenol derived chemicals, lignin monomer molecules and oxidized lignin monomers. The type of biomass from which lignin is extracted and extraction techniques directly affect the chemical structure, properties and functionality of the lignin. However the linkage between lignin types and the products types is not well understood. This depends on some complex factors such as dispersing and binding properties, colloidal properties and rheology control, as well as surface and interface stabilization [26].

2.1.5 Biorefinery process design

The strategy for development of promising product-process in a chemical industry can be based on either technology or market. New products are identified based on technology development or on market needs. The important point in both cases is to match customer need and technical innovation. One approach is the Stage-GateTM Product and Technology development framework. The main objective of this framework is to bring robust ideas to the appropriate manufacturing stage by step-wise testing [27]. The Stage-GateTM framework is similar to traditional process design development (Figure 2.3). This can be carried out in several stages by goal of minimize work and design costs by assigning the appropriate people and number of people working on the tasks.

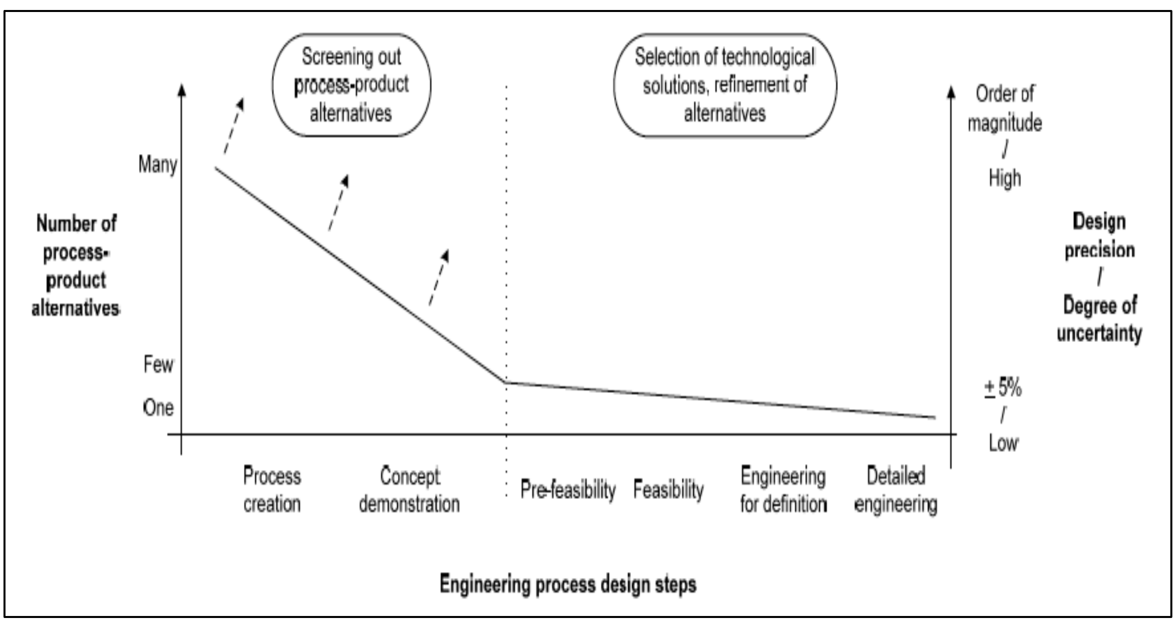


Figure 2. 3: Engineering process design development steps [28]

Incrementally from process creation to detailed engineering the level of detail in the design of the options increases. This in turn decreases the uncertainty and increase potential of cost reduction for the system [29], [28]. Generally process design includes flow-sheet synthesis, technical and economic feasibility analysis and decision making parts. Several structured techniques for conducting flow-sheet synthesis are proposed. The most popular techniques are the onion model [29]–[32]. This technique similar to algorithmic flow-sheet generation involves a large amount of computations. However instead of a computer (using heuristics), a process engineer runs the initial option generation step. According to this it can be considered as an enhanced hierarchical approach. Other methods for flow-sheet synthesis include V-model, the waterfall model and spiral model. These models split up the stage of engineering process deign in a different ways. They include comparison and iteration to mainly present the life-cycle of a process design project and prepare the required validation [33].

In green-field and retrofit plants' designs same principles and tools as described in this section are applicable. One important point about these plants is they are perusing different goals, which have to be taken into account in their design. The goal in retrofit plant is mainly improvement of existing operations. This can be achieved by capacity increase, debottlenecking, or technology upgrades. In green-field plant design the target is to have a new production facility. Retrofit design can have a same goal as green-field (e.g. implementing a new product production line next to the existing facilities). This is when it is required to consider different design restrictions (e.g. integration of the process and business of a new feedstock-process-product [34], [35] in to the existing plant).

2.2. Forest biorefinery cost estimation

Different cost estimation methods are used to evaluate economic performance of biorefinery technologies. These methods include estimation of operating and capital costs (e.g. [33]) based on modeled mass and energy (M&E) balances and process conditions.

2.2.1 Operating cost estimation

Operating cost is consisted of two categories, variable and fixed operating costs.

- The variable operating costs includes raw materials, energy and chemical. Their estimations are done based on information from similar projects or monthly inventories. In case of new technologies M&E are used to calculate this cost.

- Fixed operating cost includes administration, insurances, labor, maintenance, operating supplies, rents, other overheads, etc. These can be calculated by knowledge of the requirements to operate the system. However depreciation and taxes in category of fixed operating cost are determined on different approaches. Depreciation is calculated based on capital investment costs and estimated schedule for depreciation. Taxes are estimated within the cash flow analysis [33].

2.2.2 Capital cost estimation

There are different capital cost estimation techniques (e.g. Dysert (2003) [36], Peters, Timmerhaus et al. (2003) [37], or Seider, Seader et al. (2009) [27]). Factorial techniques are the most well-known methods for calculation of capital cost unit/system of a new technology. They apply vendors' quotes for the unit/system, different indices (Chemical Engineering Plant cost index or Marshall & Swift cost index) and several factors (e.g. material factors, installation). Equation 1 is used in unit capital cost estimation in different level of plants.

$$C = C_{ref}\left(\frac{M}{M_{ref}}\right)^{\alpha}\left(\frac{i}{i_{ref}}\right) \qquad \text{(E-1)}$$

C: is related to cost of new equipment

ref: belongs to reference of related values

M: indicates the capacity of new equipment

α: is the exponent of the capacity

i: are used as cost index.

Then sum of the purchased equipment costs are multiplied with the related factors to take into account the installation, preparation and other plant building costs. However at the final step to have more precise estimation of capital cost in case of the required equipment, contingency costs have to be considered.

2.2.3 Cost accuracy of unproven technologies

Cost misestimating (especially capital costs) decreases the quality of decision made about commercialization of unproven technologies. On the other hand this in turn makes comparison of undeveloped technologies with different stages of development (laboratory, pilot and demonstration scales) more challenging. Several models are developed to analyze the cost accuracy of pioneer technologies.

In 1965, a definition checklist was provided to estimate the contingency cost of capital projects [38]. The checklist included six principal definition categories: 1- general project basis, 2- process design, 3- site information, 4- engineering design, 5- detailed design and 6- field performance. Twenty years later when the real cost data of those projects were captured and were compared with the considered contingency. This could validate the definition checklist [39].

Later the important of above model was captures by RAND Corporation [40]–[42]. They could develop models for analysis of estimated costs and estimated production capacity. Forty-four energy technologies and chemical process plants served the required data for this model. They proposed several factors as reasons of cost underestimation for first commercial scale. Then they ran a multi-variant regression based on these factors. Therefore main factors with the highest correlation were identified. These factors are[41]:

1- Percentage and number of new technology
2- Level of project definition
3- Level of mass and energy balances' information from prior developed projects
4- Level of project complexity
5- Type of used material (solid or gas and liquid)
6- Inclusiveness and
7- Existence of impurities and
8- Wastes

Equitations 2 and 3 present, cost growth and plant performance models. These models were developed to calculate cost increase over the original estimates and production shortfalls from design capacity respectively. Each parameter of these models was introduced in Table 1.

$$\text{Cost growth} = 1.1219 - (0.00297 * \text{PCTNEW}) - (0.02125 * \text{IMPURITIES}) - (0.01137 * \text{COMPLEXITY}) + (0.00111 * \text{INCLUSIVENESS}) - (\text{C1} + \text{PROJECT DEFINITION}) \quad \text{(E-2)}$$

$$\text{Plant performance} = 85.77 - (9.69 * \text{NEWSTEPS}) + (0.33 * \text{BALEQS}) - (4.12 * \text{SOLIDS}) - (17.91 * \text{WASTE}) \quad \text{(E-3)}$$

Table 2. 1: Definition of cost growth and plant performance model's parameters [41].

Variable name	Definition	Range of value
PCTNEW	Percentage of estimate incorporating technology unproven in commericial use.	0 to 100
IMPURITIES	Assessment by industry process engineers of difficulties with process impurities encountered during development.	0 to 5
COMPLEXITY	Block count of all process steps in plant.	1+
INCLUSIVENESS	Derived from checklist measuring completeness of estimate (percentage of items included).	0 to 100
PROJECT DEFINITION	Level of site-specific information and engineering included in estimate.	2 to 8
NEWSTEPS	Number of process units that incorporate technology unproven in commercial use.	0 to total process steps
BALEQS	Percentage of heat and mass balances equations based on actual data frim prior plants.	0 to 100
WASTE	Assessment by industry process engineers of difficulties with waste handling encountered during development.	0 to 5
SOLID	Designates that a plant processes primarily solid feedstock of products.	1 if solids plant, otherwise 0

This model has been also used in techno-economic studies in biorefineries [43]–[46]. However application of these models for biorefineries are associated with some obstacles. One is that, these models were developed at a time that none of biorefinery technologies were developed. This in turn makes RAND models uncertain for biorefinery application. Another point is that RAND models are general models for all the unproven technologies. They contain some variables that are not important or are already considered in cost estimation of biorefineries (e.g. inclusiveness, impurities and wastes).

In order to have more precise cost estimation for first implementation, Southern Company Services (SCS) [47] categorized the contingencies into two groups:

- A group that should be involved in project cost estimates:
  - Scope omission and error
  - Pricing
  - Escalation
- A group that should be eliminated:
  - Schedule changes
  - Scope expansion
  - Acts of God

Thereupon SCS provided methods for estimating the first three contingencies:

- For scope omission and error: a fixed percentage based on percent engineering complete versus confidence in scope
- For pricing: Monte Carlo simulation software
- For escalation: percentage based on an annual report on anticipated escalation

Later in 2003 a mathematical model to analyze the accuracy of early cost estimation of construction projects was developed [48]. They ran a survey to gain required data for factor analysis and multivariate regression. In this survey forty-five reasons for cost misestimating were proposed. These reasons include both internal and external factors.

- Internal factors are controllable. Internal category includes factors such as percentage of new technology, level of project definition, etc.

- External factors are not under control. External category includes factors such as inflation, strikes and etc.

Using regression five important factors were identified (out of those forty-five factors). These factors are:

1- Basic process design
2- Team experience and cost information
3- Time allowed to prepare the estimate
4- Site requirement
5- Bidding and labor climate.

Level of project definition in engineering design steps can address the four first factors [28]. Moreover the fifth factor is considered as an external factor. It is noteworthy to mention that this this study aims to elaborate more on the effects of internal factors rather than external factors. The reason is that cost estimators are responsible to consider controllable factors of cost misestimating.

More recently in 2005, the Independent Project Analysis (IPA) Inc. website [49] introduced two factors to calculate required contingency for the capital cost of project. These factors are project definition level and percentage of new technology. Moreover they developed a model to underline these factors. In this model it is shown that all the unproven technologies are underestimating cost (most of them 60 % lower).

2.3 Experience curve approach

Experience curve approach predicts costs trends of technologies at commercial scale. This method can provide valuable information for decision makers. The reason is that they will be able to evaluate long-term competitiveness of technologies.

2.3.1 Definition

Experience curve is an empirical approach. This has been used for analyzing the future cost paths of new technologies for several years. The experience curve definition is based on the learning curve. Learning curve illustrates labor cost reduction in variable of number of standard products produced. This has to be taken into account in an individual company [50]. However experience curve is a more general concept than learning curve. It can show costs reductions of non-standard products, which are produced globally, or even in an individual company.

The cost that experience curve addressed is the total cost. This includes research and marketing, administrative, labor, capital costs etc. Main drivers of cost reduction are:

- Changes in the production (because of innovations, scaling and learning effects)
- Changes in product (because of product design, standardization and innovations),
- Changes in the input price

2.3.2 History of Experience curve

The first use of experience curve backs to 1936 when an aircraft company found that the unit labor cost decreased in a constant rate by every doubling of cumulative production. Then they used this for their future cost development trends. Today learning curve is the graphical shape of that discovery [51].

Then in 1966 Boston Consulting Group considered the production cost dynamics as a function of cumulative productions in terms of technological learning. In fact that dynamics as a function of cumulative productions is experience curve approach [51].

2.3.3 The classical methodology of experience curves

In general experience curves explain how the total cost (including operating and capital costs) will decrease by every doubling of cumulative products. This can be explained by a constant and predictable percentage, which is progress ratio (PR). The main equation to describe experience curve is [52], [50]:

$$C_n = C_0 * \left(\frac{CUM_n}{CUM_0}\right)^b$$

(E-4)

C_n: The cumulative costs

C_0: The first product cost

CUM: The cumulative production

b: Experience index

This is used to present the relation between production cost reduction and cumulative production.

2.3.4 Progress ratio (PR)

PR is function of experience index (as it shown in eq. 5 and 6). Experience curve is defined by PR. It shows the cost reduction in every specific technology. PR of 70% means that the cost reduction by each production doubling is 30% (see figure 2-4).

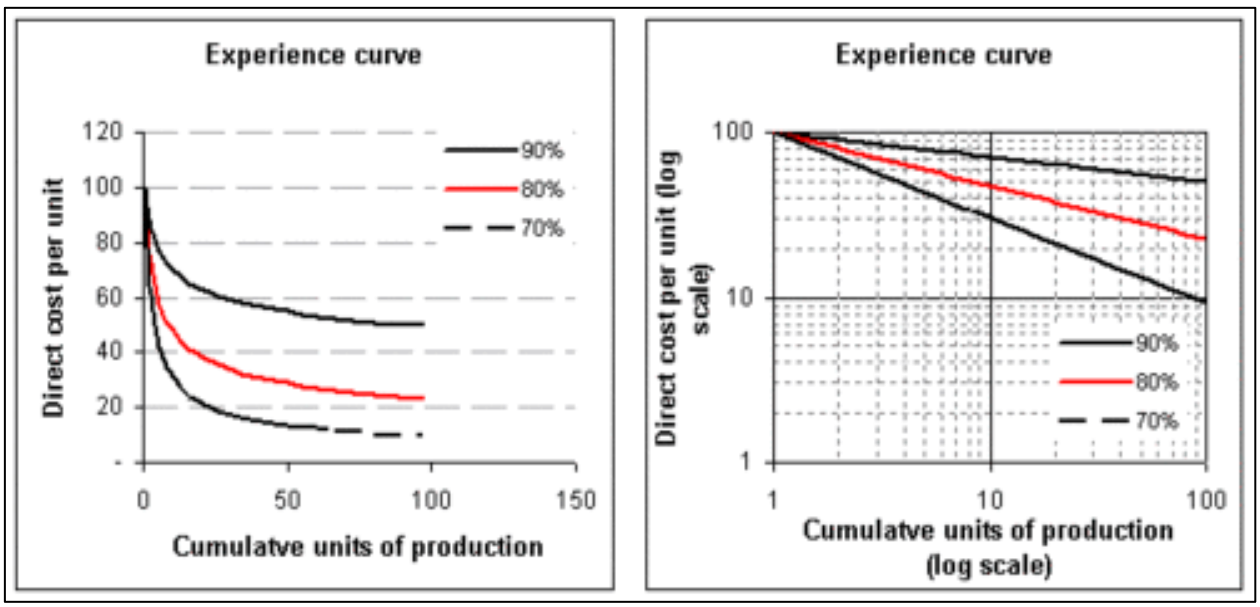


Figure 2. 4: Experience curves with PR of 70%, 80% and 90% [53].

The PR for various technologies has been calculated. Generally it is in range of 65% to 100%.

$$PR = \frac{C_{CUM2}}{C_{CUM1}} = \frac{C_0 * CUM_2{}^b}{C_0 * CUM_1{}^b}$$

(E- 5)

So in case of C_{cum2}= C_{cum1} PR equation would be:

$$PR = 2^{b}$$

(E-6)

In general PR obtained by minimization of the sum of squares. Therefore in order to consider the error of this fitness, coefficient of determination (R^2) is used. R^2 is ratio of regression sum of squares to total sum of squares.

- $R^2 > 80\%$: fitted data are correlated
- $R^2 < 25\%$ fitted data are not enough correlated

Another important error is standard PR error (σ_{PR}). This is calculated by propagation theory. This theory is shown in eq. 7 [54].

$$\sigma_{PR} = ln\, 2 * PR$$

(E-7)

The coefficient of determination and the standard progress ratio error are mostly calculated by Sigmaplot software instead of Microsoft Excel software because it showed some problems for calculation of R^2 and σ_{PR} [54].

In some cases PR showed incremental trends of cost (PR>100%). An example of this exception is nuclear technology (fig. 2.5). The progress ratio of more than 100% means that costs do not decrease by every doubling of cumulative production. This happens when rate of total cost reduction (derivers of cost reduction as mentioned above) is not as fast as the rate of cost increase. This could be due to safety and environmental regulations.

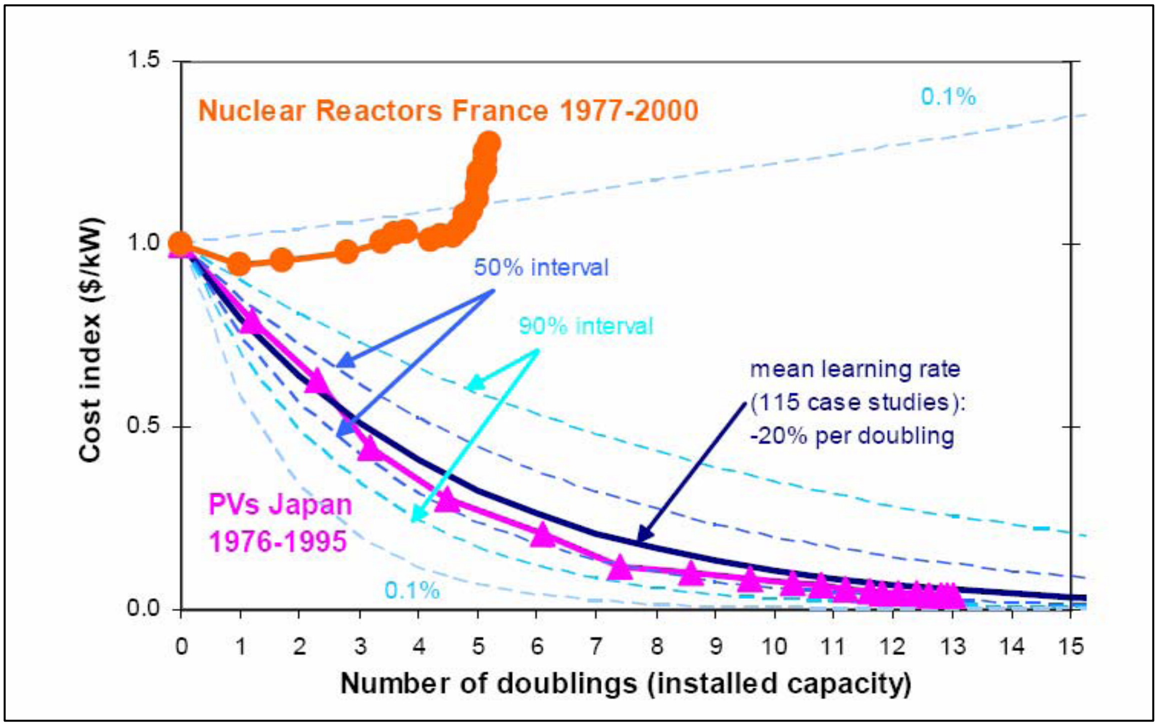


Figure 2. 5: Incremental trend of experience curve in nuclear power technology [50]

This exception in PR proves that experience curve has limitation for non-standard products application. This can also show that experience curves is an approach to predict cost trends and not necessarily to predict cost reduction [50], [51], [55].

Moreover experience curves are not always straight lines. They may have some breaks (see fig. 2-6). This is mainly due to non-symmetrical relationship of price or cost, and technology innovations (radical changes not marginal).

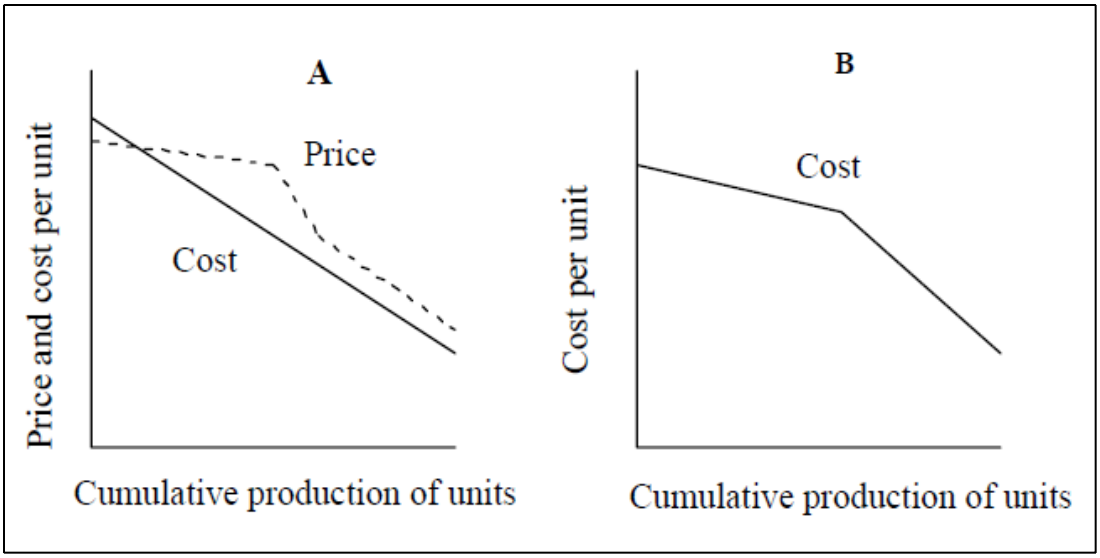


Figure 2. 6: Breaks in experience curves. [50]

The breaks in experience curve may refer to the changes in prices, products demand and market, development in technology. In this experience curve, it is suggested to separate the curve at the point that it breaks.

Experience curves explain the rate of cost reduction in various energy technologies. Moreover they show that rates of cost reductions depend on products modularity [50]. Consequently experience curves are different from one kind of product to another kind of product and from one firm to another firm [55]. In the smaller and modular products, cost reduction rate is more rapidly than non-modular and bigger products. The reason is that in manufacturing smaller products the available opportunities to improve technology and to reduce costs are more than manufacturing bigger products.

Experience curves proved that for the cost reduction an initial market is required by which learning can be obtained. The initial market can be developed through government policy about supporting the development of new technologies. Thus through the times costs of new products can decrease [50].

2.3.5 Experience curves challenges

1- In analyzing this tool every relevant parameters that result in cost reduction should be isolated and their effects should be calculated. This is challenging task, because it needs a lot of data and cooperation between science and industry [51].

2- Concept of the experience curve changed through the time. In the past it was used for the man-hour cost per unit of the standard products in an individual company. Now it is used for the analyzing and forecasting the cost reduction in the future. Moreover this is not only for the standard products and in the individual company but also for the nonstandard products and global and national companies. As a result these factors that are not considered, increase the uncertainty of the results obtained from experience curves [50].

3- Experience curve approach is used for predicting long-term cost paths. However in a high uncertainty conditions, it is not proper for the long-term cost prediction. This is due to the fact that it decreases the quality of prediction. Generally it is better to be used for 5-7 years prediction [50].

It is important to mention that even a small mistake in the progress ratio leads to reaching different break-even point or cost-competitiveness [56].

2.3.6 Experience curve for energy technologies

In 2006 New Energy Externalities Developments for Sustainability (NEEDS) [50] carried out a project to review experience curve of energy technologies. Energy technologies include wind, water, solar, nuclear, etc. The main objective of this study was to provide a systematic framework for cost prediction of new energy technologies. Hence to achieve this objective they compared three methods of cost forecasting:

1- Experience curve
2- Bottom up analysis: in this technique the total cost improvement, a technology can gain has to be identified. Then this minimum cost is connected to its maximum cost. However a methodological approach to show this method is missing.
3- Expert assessments: in this approach costs are predicted based on judgments of people who are experts in the technology. In this approach it is suggested to combine this

method with other methods. This in turn helps to evaluate the predicted cost development paths from other techniques.

At the end they suggested to use all the three methods together to have more precise cost prediction. Moreover in the suggested framework a range of PR for experience curve instead of one fixed number is more recommended. The reason is decrease level of uncertainty in energy technologies (which are mostly new technologies). Following paragraph presents a technology example (Combined Heat and power (CHP)) from this review:

Bio-energy technologies such CHP plants utilize the range of bio-energy sources. These include energy from woods (that are grown explicitly for energy purposes), residual wood from forests, herbaceous matter (e.g. straw, perennial grasses, and cereals) and etc. It is important to mention that all types these resources have not been used in NEEDS project. They announced that there is not too many experience curve studies on bio-energy technologies. For example according to their reviewed literatures the PR for experience curve of CHP combustion plant was estimated to be 75% (by an initial cumulative capacity of 102.5 MW) and 91% (assuming zero initial capacity) [57]. Also the PR for experience curve of wood-fuel supply chain, or Primary Forest Fuel (PFF) was 85% based on data from different types of supply chains (terrain, roadside and terminal) [58].

In 2009 another study was carried out to predict experience curve of Brazilian corn ethanol production. In this study they suggested to divide the experience curve of a total production cost into its main drivers; feedstock costs and costs excluding feedstock costs. Figure 2-7 and 2-8 present these experience curves [52].

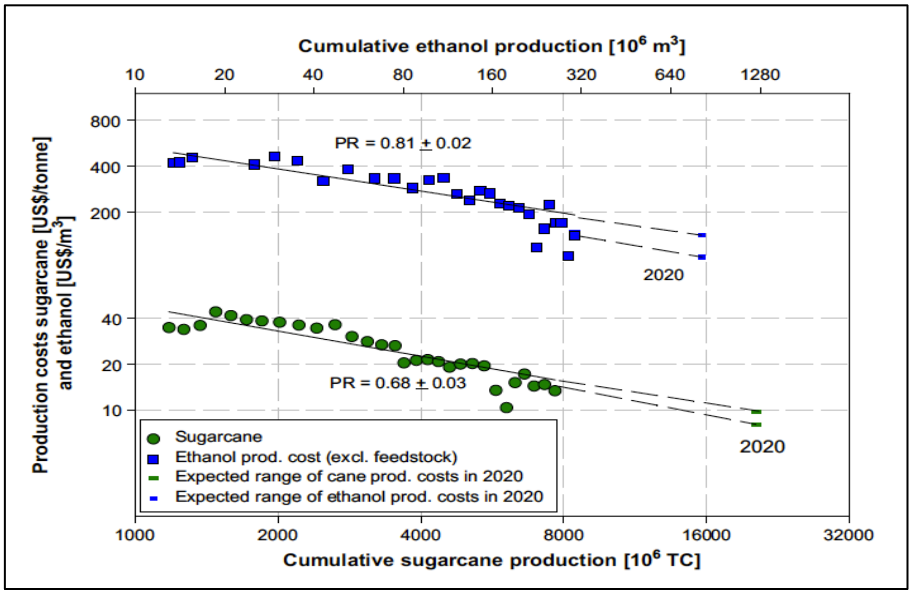


Figure 2. 7: Experience curves for sugarcane and ethanol production (excluding feedstock costs) [53].

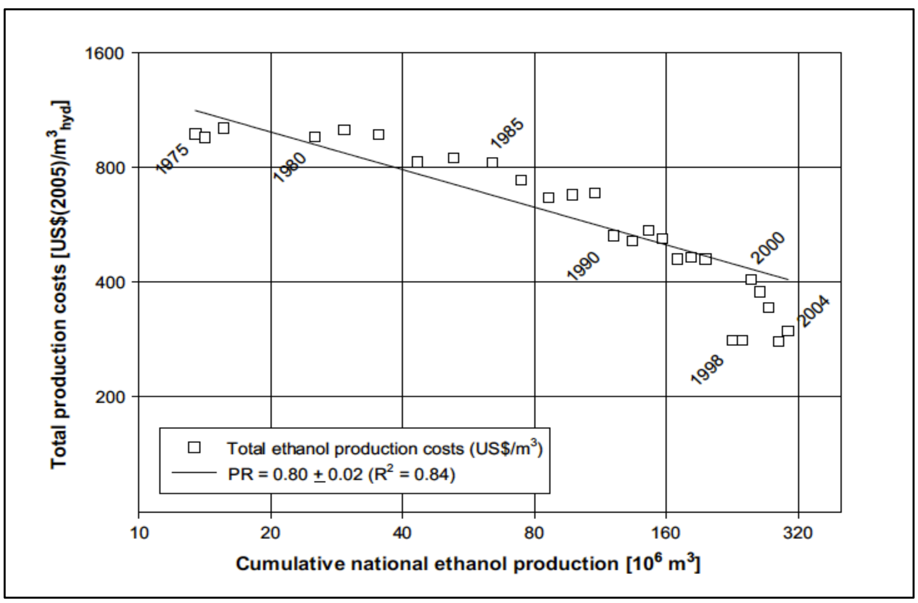


Figure 2. 8: Experience curve for total Brazilian ethanol (1975–2004) including feedstock costs [53].

Separated curves helps to have a better understanding about the cost reduction factors and also future cost developments. For example from figure 2-7, it can be understood that PR of feedstock (68%) is much less than PR of costs excluding feedstock (81%). According to this in case of combining all costs together (figure 2-8), it is not possible to identify the components of costs that have more opportunities for cost reduction.

At the same time of above study Hettinga et al. [59] carried out another study on experience curve of U.S. ethanol. They could capture the important advantage of experience curve to evaluate the technology's long-term competitiveness. According to their estimate PRs for ethanol manufacturing and corn production are 87% and 55% respectively (figures 2-9 and 2-10).

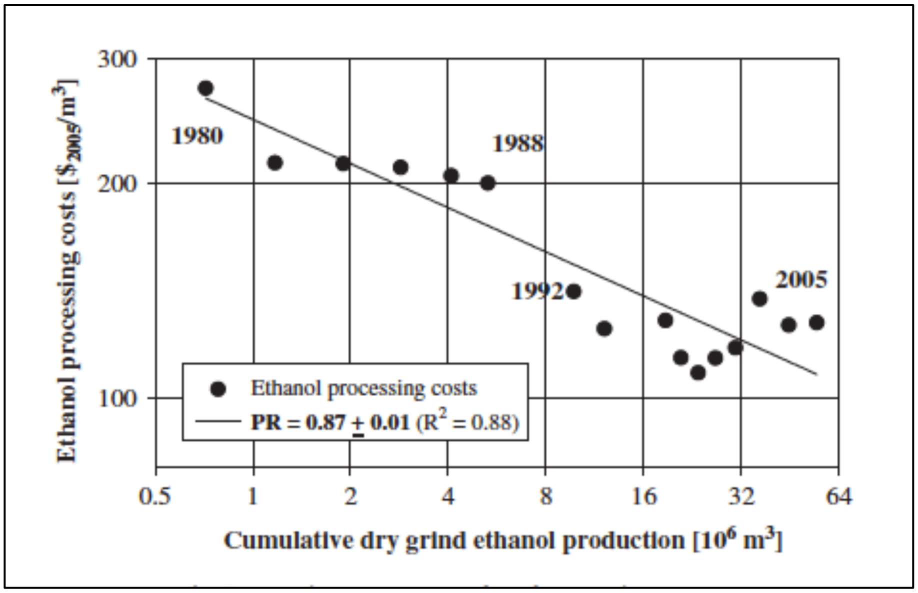


Figure 2. 9: Experience curve for ethanol processing costs [59].

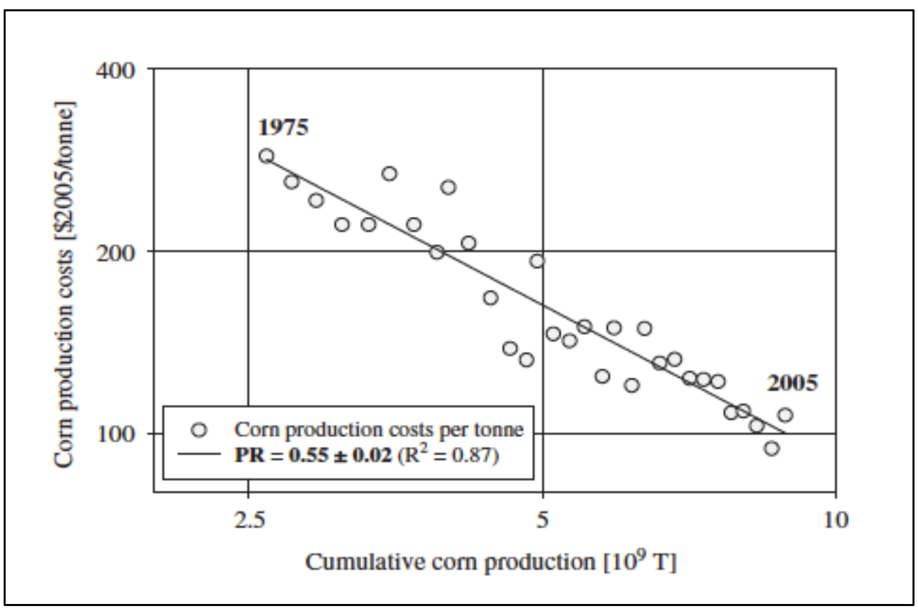


Figure 2. 10: Experience curve for corn production costs [59].

Then they captured the important advantage of experience curve to evaluate the technology's long-term competitiveness.

Application of this tool for energy supply technologies is widespread [60]–[64]. However this is not the same and very common for the energy demand technologies [65]–[68]. In a study by M. Weiss et al [51] the experience curves of the energy demand technologies(e.g. energy consumption of ammonia and urea production, energy consumption of ethanol production, etc.) were reviewed. They showed that cost and price decreases by PR of 82±9% which is similar to PR in energy supply technologies.

2.3.7 Experience curve and diffusion of new products

The relationship between cost reduction and diffusion of a new product is intuitive. This helps marketers to price their products easily and to reach to the optimistic markets. On the other hand Learning decreases products' prices so it speeds up the adaptation of the new products. However there is no specific relationship between experience curve and this diffusion. The reason is that the products' diffusion does not only depend on the low price of new product but also depends on the other factors such as opinions of consumers about the new products, the economic situation of the society, etc. [55].

2.3.8 How to evaluate results of experience curve

There are two approaches to assess the experience curves analysis:

1. Bottom up assessments: the individual and industrial reports can be used for identifying current and future cost reduction source. Having more reports results in better assessment.
2. Experts' cost analysis: They have complete and practical information and vision about their field. Then they can evaluate, cost predictions, which would be called technology insight [50].

2.3.9: National Renewable Energy Laboratory (NREL) approach for cost prediction

National Renewable Energy Laboratory (NREL) applied another approach inspired by experience curve to predict costs of non-commercial technologies such as lignocellulosic ethanol production [69].

In 2002 effect of economies of scale on the minimum price of ethanol from lignocellulosic biomass were assessed. They divided this in two parts: feedstock cost and non-feedstock cost. Figure 2-11 presents the results.

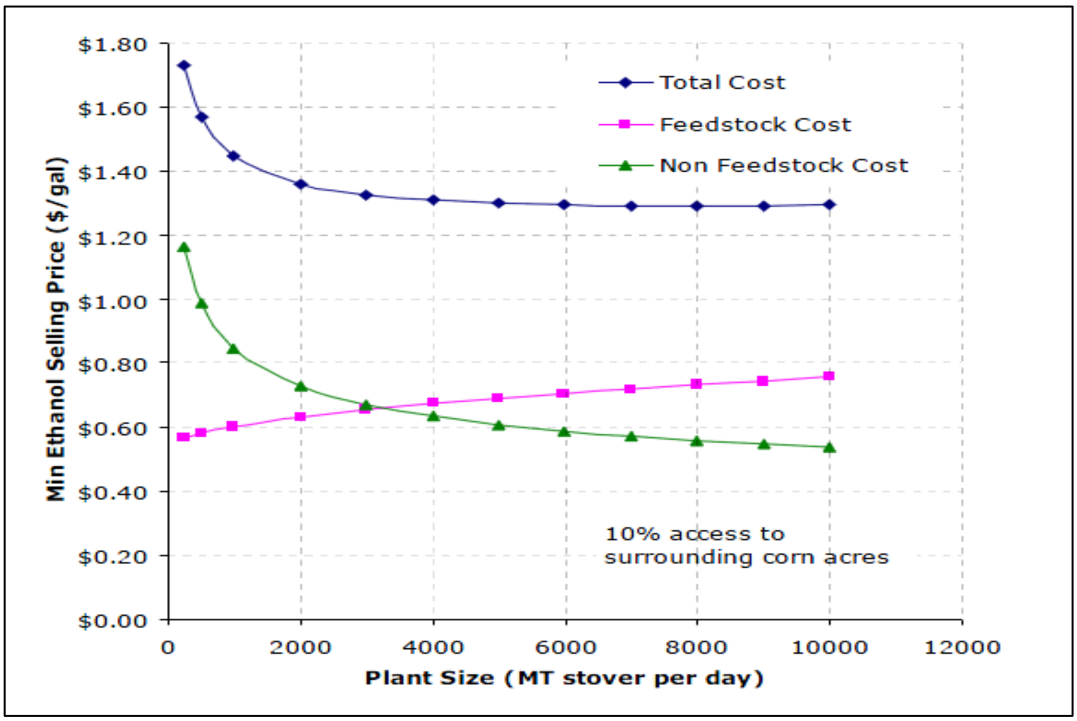


Figure 2. 11: Effect of economies of scale on feedstock and non-feedstock costs, [70].

The non-feedstock cost reduction reflects impacts of economies of scale (an increase in plant size from 2,000 to 10,000 MT per day reduces non-feedstock costs by $0.19 per gallon). However for feedstock costs, the opposite effect was happened. The reason is that there are some challenges about this type of feedstock such as transportation costs. Increase in feedstock cost eliminated $0.13 of above savings (see total cost curve). Plant sizes to the 4,000 MT per day design show rapidly increasing feedstock costs. However there is no additional cost savings above size 6000 MT. For the conservative scenario of collecting Stover from 10% of the corn acres around, the optimal minimum plant size is in the 4,000 to 6,000 MT per day range. Understanding optimal minimum plant size helps to have better planning for technologies.

Later in 2011 another study by NREL [70] applied a more comprehensive approach. They predicted cost development paths of feedstock, enzymes and conversion to depict the future minimum-selling price of ethanol. Figure 2-12 presents the results.

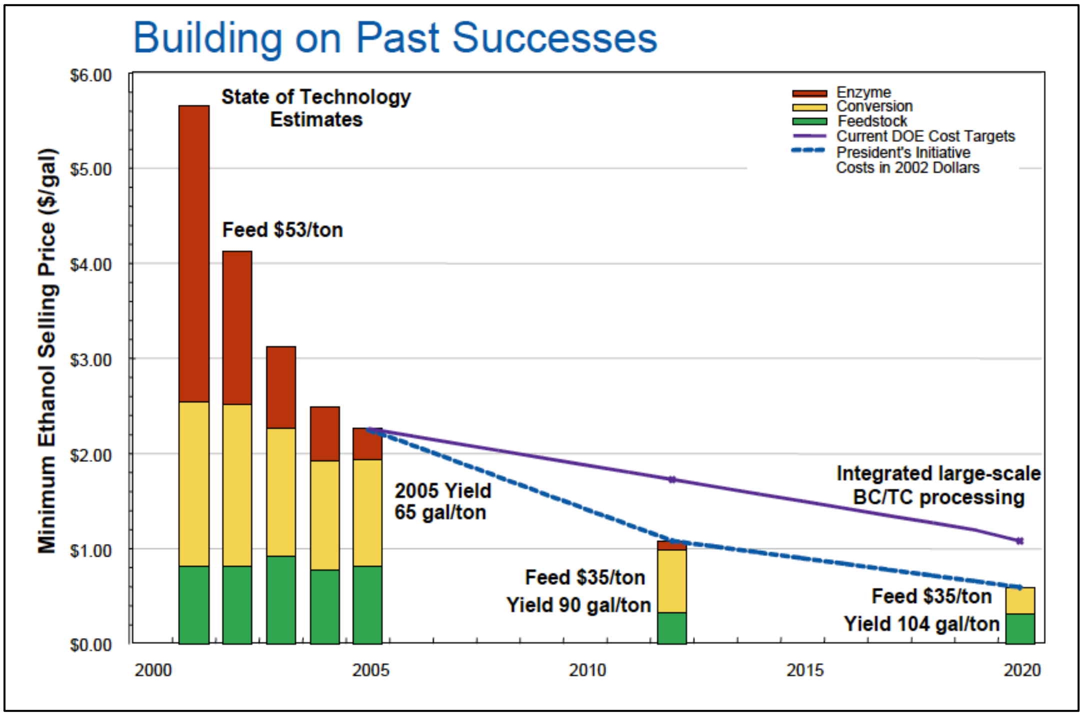


Figure 2. 12: Minimum ethanol selling price according to cost prediction of enzyme, feedstock and conversion [70].

This assessment was done particularly for the case of lignocellulosic ethanol. Their predictions for 2010 for enzyme, feedstock and conversion are 100%, 75% and 25% reductions respectively.

Despite to their valuable works for cost prediction of new technologies a systematic methodological approach is missing.

2.4. Decision making

2.4.1 Multi-Criteria Decision Making (MCDM) concept

They are some restrictions for traditional analytical tools of decision-making processes such as considering only single objective problems. This made decision makers to find a way to make decisions based on several criteria. Therefore methods such as Multi-Criteria Decision Making (MCDM) process by considering several criteria are appropriate to solve such decision problems. There are two types of MCDM model:

1. Multi-Attribute Decision-Making (MADM): In MADM problems, decision alternatives are already identified according to certain criteria and are in a limited number. According to this objective of solving MADM problems is to sort and to rank alternatives.
2. Multi-Objective Decision-Making (MODM): In MODM problems, alternatives are not identified and their number is large. Multiple objective programming can be used to solve MODM problems to identify alternatives and rank them according to the set objective(s).

Generally the applicable solutions for solving MCDM problems are as following.

1. Selecting: It includes selecting the most satisfying options among a set of alternatives.
2. Sorting: This is also called as categorizing and means categorizing alternatives by comparing them according to the set of criteria.
3. Ranking: This means prioritizing the alternatives from the most satisfying one to least one [72].

In order to apply MCDM model the steps are as following sequence:

1. Identifying decision goal(s) and decision maker(s)
2. Identifying alternatives
3. Criteria identification: Identifying criteria which are related to the decision problem
4. Scoring criteria to measure the alternatives performance against them and develop an evaluation matrix (decision table).
5. Standardization or prioritizing the criteria
6. Weighting criteria according to their importance to the overall decision
7. Ranking of alternatives
8. Sensitivity analysis

9. Find recommendation

Two first steps provide the basis for the decision-making and should be done at the very first to make a background for other steps [72].

Criteria identification: Criteria selection is a critical step in decision-making process. The reason is that it brings basis for judgments. In identifying criteria it is important to take into account following points:

- Completeness: It is important to make sure that all criteria are taken into consideration. One of useful tool is hierarchally structured value tree. This consists of 4 layers: 1- goal of decision-making, 2- main criteria, 3- sub criteria and 4- alternatives. This hierarchally structured value tree helps to check the completeness of the criteria and sub criteria. Moreover it shows that criteria and sub criteria are aligned with the set goal(s).
- Avoiding repetitiveness: Some criteria may refer to same goal and or maybe have same scores for all alternatives. These can be combined in one criterion or one can be omitted.
- Being applicable: Each criterion should be able to assess alternatives otherwise it may be possible to break down the criterion to more explicit sub criteria.
- Number of criteria: Having a large number of criteria makes situations difficult to solve the MCDM problems. Moreover it brings a lot of efforts to communicate the results. It is important to check number of criteria. However there is no “golden rule” to find the optimum number of criteria in addition to that it can vary for different applications [71].

2.4.2 MCDM problem solving methods

There are several methods to solve MCDM problem, in which most applied methods are as follows:

Analytical Hierarchy Process (AHP):

AHP is one of the mostly used method in complex decisions where quantifying of decision elements comparison is not easy. It consists of three steps [72] [73]:

1. Hierarchical decomposition: Hierarchical decomposition is breaking down the problem into hierarchy sections (goal(s), decision making criteria, alternatives).
2. Evaluation: Prioritizing alternative and criteria by comparing alternatives against decision-making criteria, and decision-making criteria against goal(s) accordingly. This can be done by a group of experts.
3. Results combination: Combining the priorities from second step to specific priorities to have the final decision

Multi-Attribute Utility Theory (MAUT):

MAUT is one of the most understandable decision making forms, which includes following steps [74]:

1. Problem identification: Alternatives and goal(s) are identified.
2. Alternatives evaluations: Alternatives are assessed by specified criteria.
3. Preference determination: Criteria are weighted (by decision makers), and normalized, and then probability of the specified criteria for each alternative is determined.
4. Alternative comparison and sensitivity analysis: Alternatives are compared by the results achieved from third step. Then sensitivity analysis is conducted to assess the alternatives against changes in the weighting of criteria.

Multi-Objective Optimization (MOO):

The main goal of MOO is to identify a set of Pareto optimal solutions Pareto optimal solutions are a set of alternatives, which are identified, based on multiple objectives. Here trade-offs are being done between two or more conflicting objectives to make the optimal decisions (Pareto optimal solution is compromise solution in MOO technique). The most used methods of MOO are as following [75]:

1. No-preference method
2. A posteriori method
3. A priori method
4. Interactive methods

However if the number of objectives increases by more than two, some challenges about visualization may occur. Then to handle that it is suggested to apply interactive methods [76].

2.4.3 Decision making and process design

Decision-making methods vary depending on the stage of the process design process (see fig. 2-3). At the very early design stage (conceptual level design analysis), the goal is to make selection decisions and to screen out less promising options. The decision-making criteria can be economic, environmental, societal, supply chain related, etc. These criteria, which are often conflicting, should consider simultaneously as a multi- criteria decision-making (MCDM) problem. Consequently to solve this problem at conceptual level, one approach is to consider only one criterion and make all decisions based on that. Another approach is to use each criterion one by one i.e. by each criterion screen out numbers of less promising alternatives and then using other criteria as well. Methodologies are developed to solve MCDM problem at the early stage of the design e.g. by Hytönen and Stuart [77]. They proposed LBA as an evaluation methodology. This considers project performance and project risk individually for alternative biorefinery options into the forest industry. Thus this is subjective screening based on the two criteria.

At pre-feasibility level in which more accurate data are available, more sophisticated decision making methods are used. This is not only for selecting promising design alternatives but also mostly for ranking them. As an example of these methods, multi-objective optimization including risk analysis was proposed by Hoffmann et al. [78] to screening of chemical process technologies.

2.5 Gaps in the body of knowledge

Based on the reviewed literatures the following gaps in the body of knowledge were identified:

- Experience curve methodology has been used for many decades, and in the literature it has been even applied for the biorefineries. However as this critical point of time it is important to recognize two key factors that make it adapt experience curve to correctly assess and compare biorefinery strategies:
    - The PRs in classical experience curve are evaluated on ad hoc basis.
    - First factor is that new biorefinery strategies are immerging, on a regular basis they are existed in pilot and demonstration scales, and even first commercial scale is recently implemented.
    - Second factor is that in the last decades, whereas large enterprise was historically responsible for most process and product innovations there has been large shift especially in North America such that innovation is increasingly developed by small enterprises. Depending on many factors such as knowledge of design, process, leadership etc. this small enterprises can corporate different degrees of optimism in the cost that they present to industry.
- Early stage capital and operating cost are discussed regularly in the literature for early design and decision making, however although it is recognized in design that capital and operating costs will change (reduced) in subsequent implementation following the first commercial scale, and although it is known that technology providers are optimistic to varying extent. This has not been considered systematically in decision-making criteria at early design stage so a practical methodology to do this should be developed using a case study context.

Consequently a model should be proposed that addresses above gaps. This model directly takes into account the effect of key factors which influence the estimated cost of both first commercial scale plant (cost underestimation) and the future biorefinery costs (cost reduction).

CHAPTER 3: OVERALL METHODOLOGICAL APPROACH

3.1 Overall methodology

The methodological approach that has been used in this thesis project is shown in figure 3-1. The major steps of the methodology and case studies are described in more detail in this section.

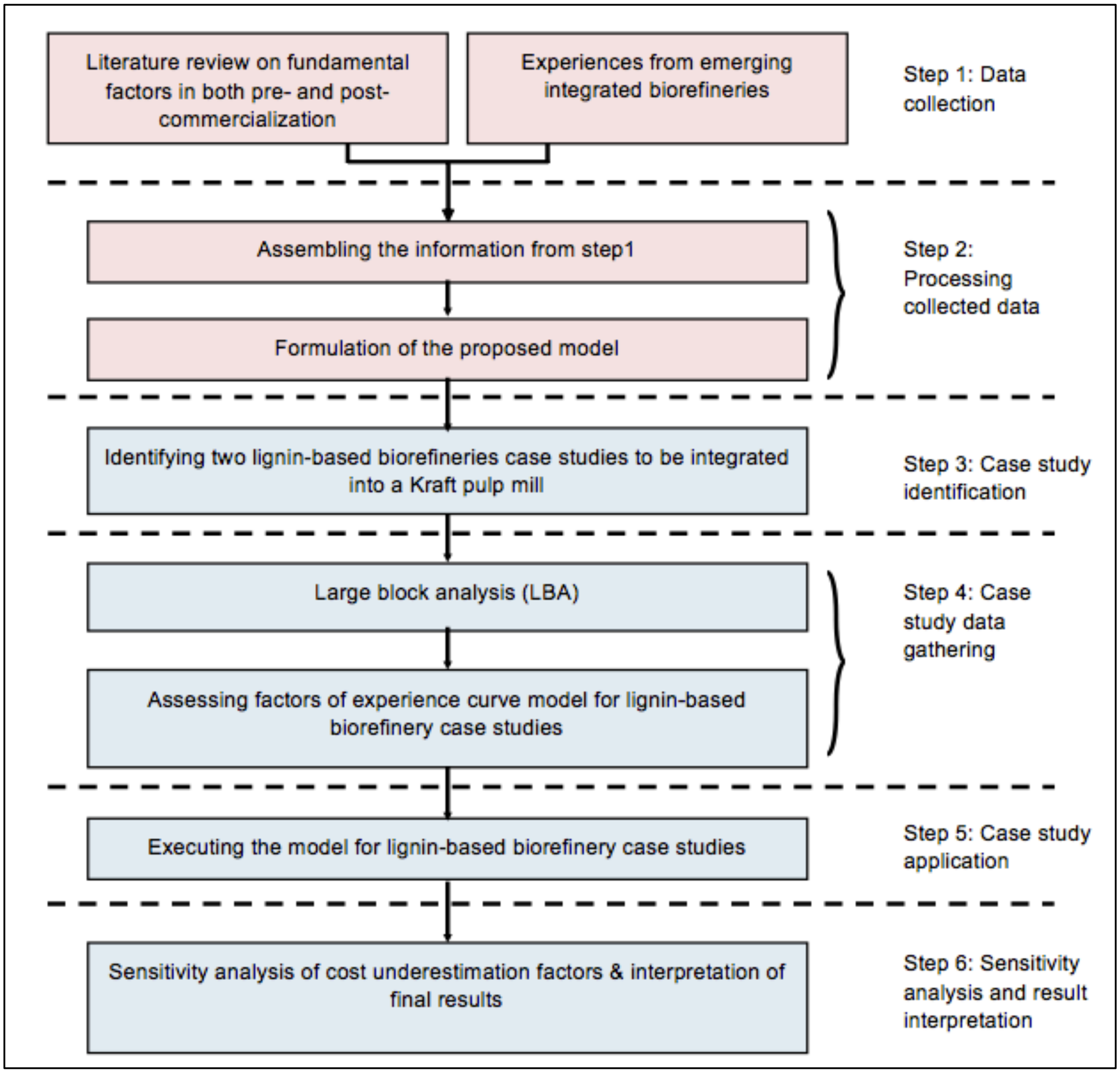


Figure 3. 1: Schematic representation of the methodology. Red boxes include tasks done to propose the experience curve model. The blue boxes contain tasks carried out to apply the model to the lignin- based biorefinery case studies.

The overall methodology of this project consists of six main steps:

1. Data gathering
2. Treating the gathered data
3. Case study identification
4. Case study data gathering
5. Case study application
6. Result interpretation

3.1.1 Data gathering

Three groups of information were reviewed:

- Literatures on reasons of cost misestimating for the first commercial scale and developed accuracy analysis models.
- Literatures on reasons of cost reductions at post commercial scale and principals of experience curve approach.
- Experiences in case of emerging biorefinery technologies such as lignin- based biorefineries for before and after commercialization.

3.1.2 Treating the gathered data

The critical information from step one of this methodology was carefully assembled:

- First source of information was assembled with third source of information to underline analysis of early state cost estimation of biorefinery technologies at their current stage of development (pre-commercial scales).
- Second source of information was also assembled to third source of information to address cost trend of post commercial scales.

3.1.3 Case study identification

Biorefinery case studies that are suitable to be applied to the proposed model of experience curve were identified, which had to have these two main characteristics:

- Emerging: biorefinery technologies that are associated with new technologies that are currently developing or will be developed over the future years.

- Different stage of development: case studies had to be at different stage of development, to assess effect of stages of development on level of accuracy of estimated cost for first commercial scale.

3.1.4 Case study data gathering

Once the suitable case studies were identified, the required data to be used in proposed model of experience curve were gathered from two parts:

- Mass and energy balances of lignin based biorefinery processes are calculated in Large-Block Analysis method [79] by input–output-models. Then results of this section are used to calculate the capital and operating costs of the case studies through traditional techno-economic analysis.
- Factors of experience curve were assessed for the case studies:
  - Cost underestimation factors for first commercial scale:
    - New technology
    - Appreciation for and level of design engineering
    - Appreciation for risk associated with integration and scale up
    - Optimism bias of the technology and project developers) and
  - Cost reductions factors at post-commercial scales:
    - Economies-of-scale
    - Process operation optimization due to learning
    - Process design optimization and less conservatism in design due to learning
    - Process improvement with new technology additions post-implementation.

3.1.5 Case study application

The gathered data from step four were fed in to the experience curve model. In this step Microsoft Excel spreadsheets were used to plot out the final graph of the experience curve.

3.1.6 Result interpretation

Then the final part of the last step was to interpret the achieved results of the experience curve model for the biorefinery strategy decision-making.

CHAPTER 4: PUBLICATION EXECUTIVE SUMMARY

4.1 Synthesis

This synthesis includes the results of the work done in this M.Sc. project in two main parts:

1) Proposed model of experience curve for emerging biorefinery technologies
    a. Models for estimating actual total cost per unit of product and errors of cost estimation of first commercial scale of emerging biorefineries.
    b. Model of experience curve for emerging biorefinery.
2) Results of applying the experience curve model to lignin-based biorefinery case studies.

4.1.1 Proposed model of experience curve for emerging biorefinery technologies

4.1.1.1 Models for estimating actual total cost per unit of product and errors of cost estimation of first commercial scale of emerging biorefineries

Four main drivers of cost underestimation at pre-commercial scales were identified (fig. 4-1).

Factors of cost underestimation at pre-commercial scales:

a. New technology
b. Appreciation for and level of design engineering
c. Appreciation for risk associated with integration and scale up
d. Optimism bias of the technology and project developers

Figure 4. 1: Fundamental factors of cost underestimation before commercialization

- New technology: Technologies that are not implemented at the commercial scale and are associated with various uncertainties.

- Appreciation for and level of design engineering: Definition level of a project according to the engineering process design stage, e.g. prefeasibility, feasibility, definition and/or detailed engineering and construction.

- Appreciation for risk associated with integration and scale up:
  - Integration risks are related to impact core business, e.g. materials handling, steam and power consumption and generated waste.
  - Scale up risk refers to comparison of the current existing scale and the targeted scale at commercialization. Also a plant with a large number of units ("complexity") will have a higher risk level.
- Optimism bias of the technology and project developers: A bias related to the personality, knowledge and experience of the technology developer and project developer. This factor can be quantified using a relative scale by several questions that can be asked during the industry partners' interviews such as:
  - Describe how technology developers over-value their technology?
  - Describe how forestry companies under-value new technologies?
  - Describe how do you believe optimism bias effects cost estimates prior to commercialization?
  - How do you address this bias relative to your technology?

Based on these factors model of estimating actual total cost per unit of product of first commercial scale of unproven technologies was proposed (eq. (1)):

$$\text{Actual total cost per unit of product} = \frac{\text{Actual annual capital expenditure }\big(\text{eq. }(2)\big) + \text{Actual annual operating cost (eq. (3))}}{\text{Estimated annual production capacity}} \quad \text{(E-1)}$$

Above equation contains two models:

$$\text{Actual annual capital expenditure} = \frac{\text{Estimated annual capital expenditure}}{\text{a} * \text{Known technology} + \text{b} * \text{Project definition}} * \frac{1}{(1 - \text{Risks'score}) * (1 - \text{Optimism bias})} \quad \text{(E-2)}$$

$$\text{Actual annual Operating cost } = \frac{\text{Estimated annual operating cost}}{(1 - \text{Risk'score}) * (1 - \text{Optimism bias})} \quad \text{(E-3)}$$

Equation 4 calculates the errors or cost overrun in cost estimation of first commercial when technologies are in pre-commercial scale. In this equation e_p refers to error in cost estimation of technologies that are pilot scale, and e_D refers to errors in cost estimation of technologies that are in demonstration scale.

$$e_P \text{ or } e_D = Actual\ total\ cost\ per\ unit\ of\ product\ (eq.(1)) - \frac{Estimated\ annual\ capital\ expenditure + Estimated\ annual\ operating\ cost}{Estimated\ annual\ production\ capacity\ for\ first\ commercial\ scale} \quad \text{(E-4)}$$

Table 4. 1: Actual total cost per unit of product for first commrcial scale' and e_P or e_D equations' parameters. The important point in quantifying these parameters is that their ranges of values are relative for the biorefinery options. Therefore these numbers only are used to relativlely make distinction between the biorefinery candidate.

Variable name	**Model**	**Range of value**	**Paramete r estimate**
Estimated annual production capacity, ($/year),	According to the model proposed by "plant design and economics for chemical engineers" [37].	0 to total process production	n.a

<table>
<tr><td>eq. (1) & (4)</td><td colspan="2"></td><td>capacity</td><td></td></tr>
<tr><td>Estimated annual capital expenditure, ($/year), eq. (2) & (4)</td><td colspan="2">According to the model proposed by “plant design and economics for chemical engineers” [37].</td><td>0 to total process capital cost</td><td>n.a</td></tr>
<tr><td>Known technology, (%), eq. (2)</td><td colspan="2">$$\text{Known technology} = 1 - \frac{\text{Investment in new technology}}{\text{Total project investment}}$$ [49]</td><td>0 to 100</td><td>a=0.5</td></tr>
<tr><td>Project definition, (%), eq. (2)</td><td colspan="2">According to percentage of engineering design a technology completed [49]. E.g. for prefeasibility: 40%, feasibility: 60, engineering for definition: 80, detailed engineering: 100.</td><td>40 to 100</td><td>b= 0.5</td></tr>
<tr><td rowspan="2">Risk score, (dimentionless), eq. (2) & (3)</td><td colspan="2">$$Risks'score = 0.5 * Scale\ up\ risk + 0.25 * Mass\ integration\ risk + 0.25 * Energy\ integration\ risk$$</td><td>0 to 0.9</td><td>n.a</td></tr>
<tr><td>Scale up risk</td><td>Judgment based, using a relative scale.
E.g. relative to the most similar commercial project:

1. If numbers of different unit of operation is 2 or less than 2, the risk score is 0.
2. If it is between 2 and 10, for each number of unit more than 2, value of 0.01 should be added to 0.</td><td>0 to 0.09</td><td>n.a</td></tr>
</table>

		However numbers of different units should not be more than 11, otherwise it shows the technology is prone to have a high risk at the time of implementation.		
	Mass integration risk	Judgment based, using a relative scale. E.g. if there is a linkage between a new process and a pulp process, that can potentially result in negative impact in the core business, the risk score is 0.02. However this risk is eliminated through in-situ testing.	0 or 0.02	n.a
	Energy integration risk	Judgment based, using a relative scale. E.g. relative to energy system of a targeted pulp mill: 1. If the energy requirement of new process is equal or less than the existing energy system, the risk score is 0. 1. If it marginally exceeds the design capacity of the turbines or boilers, the risk score is 0.06. 2. If it significantly exceeds the design capacity of the turbines and boilers, the risk score is 0.16. However this risk is eliminated	0, 0.06 or 0.12	n.a

	through capital expenditure.		
Optimism bias, (dimentionless), eq. (2) & (3)	Judgment based, using a relative scale. E.g. relative to other considered biorefinery integration options in a pulp mill, in case of amount of time elapsed in the project, level of maturity of the technology, having interfaces with other energy companies, etc.	0 to 0.08	n.a
Estimated annual operating cost, ($/year), eq. (2) & (4)	According to the model proposed by "plant design and economics for chemical engineers" [37].	0 to total process operating cost	n.a

n.a.-not applicable

4.1.1.2 Model of experience curve for emerging biorefinery

Four main drivers of cost reduction in post commercial were identified (fig. 4-2).

Factors of cost reduction commercial scales:

a. Economies-of-scale
b. Process operation optimization due to learning
c. Process design optimization and less conservatism in design due to learning
d. Process improvement with incremental new technology additions post-implementation

Figure 4. 2: Fundamental factors of cost reduction after commercialization.

At commercial scale, by every additional implementation of a technology, the project costs will decrease. This is generally continuous for many years, especially for commodity product manufacturing. The main divers of cost reduction following to first commercial scale are:

- Economies-of-scale: The annualized capital cost and fixed operating cost per unit of production decreases with increased process capacity, to different extents depending on the principal of design and operation.

- Process operation optimization due to learning: The operating cost of new processes decrease on a unit production basis considering key variable cost components such as raw material and maintenance costs.

- Process design optimization and less conservatism in design due to learning: Designers over-compensate for the first commercial scale to mitigate technology risk (i.e. the lowest possible cost is of secondary importance). Following the first commercial implementation, a more aggressive design approach can be taken due to learning and experience from previous implementations.

- Process improvement with new technology additions post-implementation: Incremental improvement innovations are typically considered after the first commercial implementation that results in lower capital and/or operating costs. They are implemented in successive projects to mitigate risk and as new ideas emerge based on operating experience.

In order to apply the experience curve approach to emerging biorefineries, some adaptations are required due to lack of commercial scale historical data for future cost predictions:

- Estimating the first commercial cost by the proposed model of actual total cost per unit of product (eq. 1).
- Calculating progress ratios based on effects of cost reduction factors (each of these factors is described in table 2).

Table 4. 2: The main drivers of cost reduction at commercial scale

Variable name	Model	Range of value
Economies-of-scale, (%)	Fixed operating cost: case-by-case assessment	0 to 100

	Capital cost [37]: $C = C_{ref}\left(\frac{M}{M_{ref}}\right)^{\alpha}\left(\frac{i}{i_{ref}}\right)$	0 to 100
Process operation optimization due to learning, (%)	Case-by-case assessment related to cost reduction rate of following sections: • Labor cost • Raw material cost • Maintenance cost	0 to 100
Process design optimization and less conservatism in design due to learning, (%)	Case-by-case assessment related primarily to: • Uncertainty in design parameters. • Complexity of the overall process.	0 to 100
Process improvement with new technology additions post-implementation, (%)	Case-by-case assessment based on identified incremental new technology changes.	0 to 100

C is related to cost of new equipment,
ref belongs to reference of related values
M indicates the capacity of new equipment
α is the exponent of the capacity
i are used as cost index.

Figure 4-3 presents the experience curve model (right side the curve is expressed by eq. 5, 6 and 7 [80]) for emerging biorefinery strategies. This is can be used:

1. To analyze total cost estimation of first commercial scale (lefts side of the curve; before first commercial scale)
2. To predict cost development trends following to the first commercial scale (right side of the curve).

$$C_n = C_0 * \left(\frac{CUM_n}{CUM_0}\right)^b \quad \text{(E-5)}$$

$$b = \frac{Ln\frac{C_n}{C_0}}{Ln\frac{CUM_n}{CUM_0}} \tag{E-6}$$

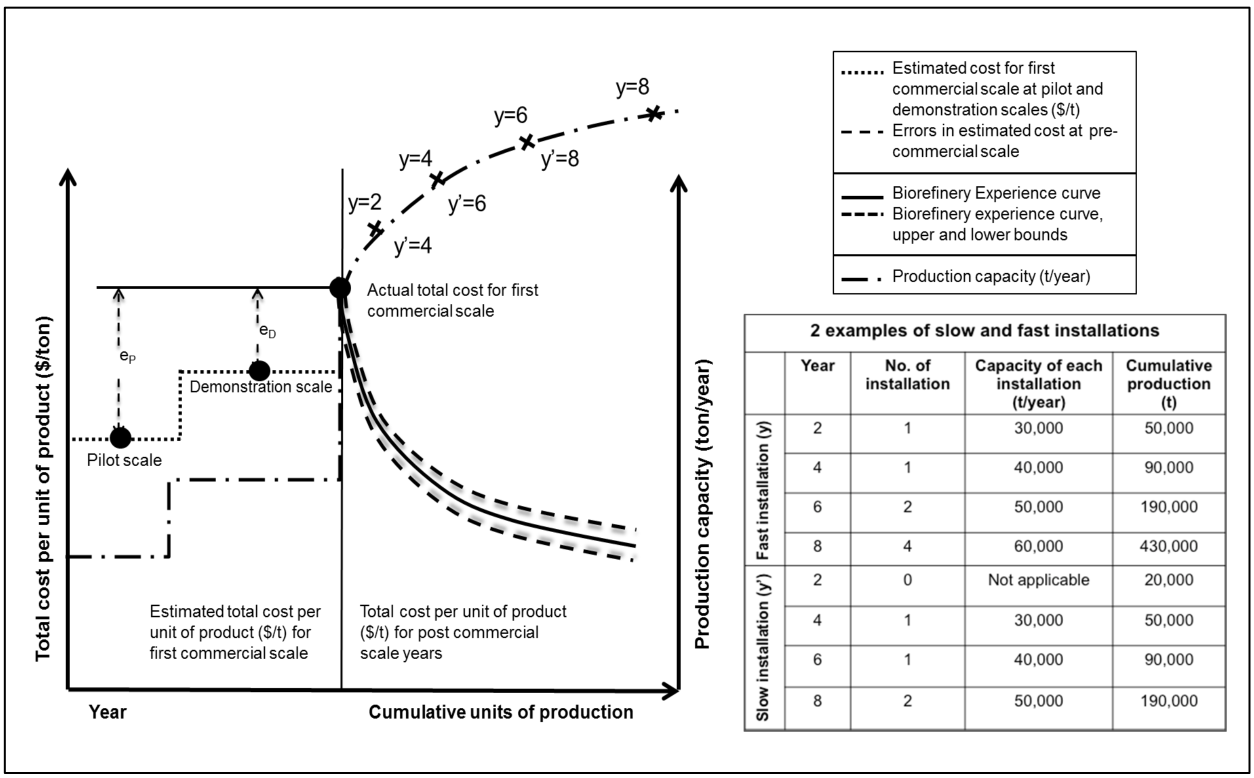
$$PR = 2^b \tag{E-7}$$

C_n: the cost per unit as a function of output

C_0: the cost of the first unit produced

CUM: the cumulative production over time

b: the experience index



2 examples of slow and fast installations

	Year	No. of installation	Capacity of each installation (t/year)	Cumulative production (t)
Fast installation (y)	2	1	30,000	50,000
	4	1	40,000	90,000
	6	2	50,000	190,000
	8	4	60,000	430,000
Slow installation (y')	2	0	Not applicable	20,000
	4	1	30,000	50,000
	6	1	40,000	90,000
	8	2	50,000	190,000

Figure 4. 3: The proposed model of biorefinery experience curve. e_P: error in estimation of total cost of first commercial scale when a technology is in pilot scale. e_D: error in estimation of total cost of first commercial scale when a technology is in demonstration scale. y: year.

4.1.2 Results of applying the experience curve model to lignin-based biorefinery case studies

The two lignin-based biorefinery case studies for experience curve model application are:

- Technology 1: Solvent pulping, Pilot scale

This is a standalone technology for integration into a Kraft P&P mill. It uses solvents to extract specific components (e.g. hemicellulose) from wood chips. Through this process these components are converted to Phenol-Formaldehyde (PF) resin precursor, sugar syrup, ethanol and acetic acid.

- Technology 2: Lignin precipitation, Demonstration scale

This technology utilizes black liquor from a Kraft P&P mill. The main process is to extract lignin by acid precipitation. This extracted lignin is used to produce PF resin precursor. Then liquor is returned to the recovery cycle.

Figures 4 and 5 and table 4-3 show results of executing LBA on the case studies.

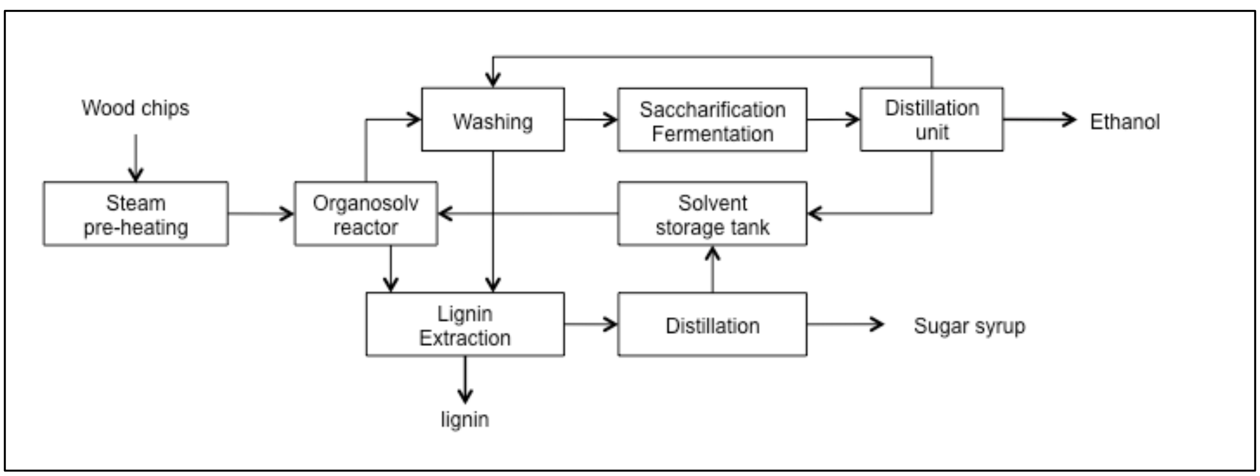


Figure 4. 4: Block flow diagram of solvent pulping process

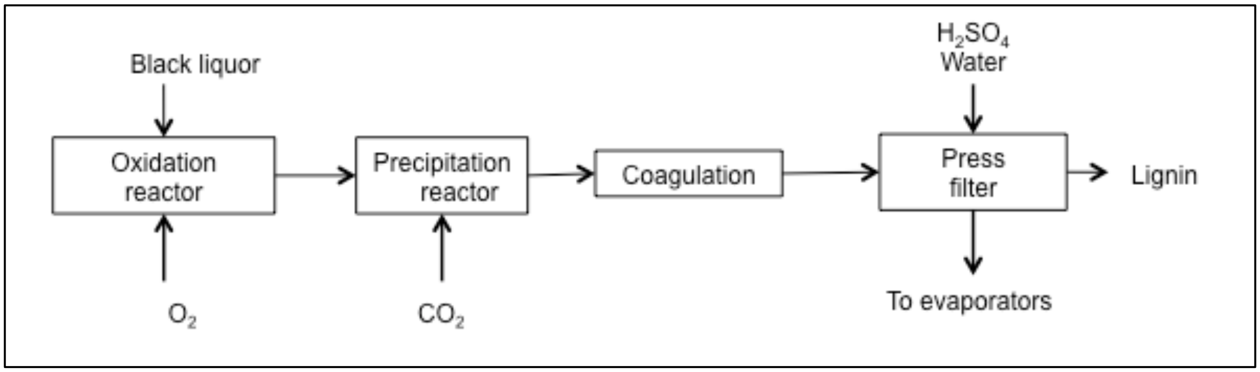


Figure 4. 5: Block flow diagram of lignin precipitation process

Table 4. 3: Values for estimated annual total capital cost, annual total operating cost and annual total production capacity

Variable name	**Solvent pulping process**	**Ligning precipitation process**
Estimated annual capital expenditure (m$/year)	36	3
Total project investment (direct capital cost), (m$/year)	19	2
Estimated annual operating cost (m$/year)	263	61
Estimated annual production capacity (ton/year)	480,000 (38% PF resin precurser,36 % sugar syrupt, 23% ethanol, 3% acetic acid)	48,000 (100% PF resin precurser)

Table 4-4 present values for:

- Cost underestimation factors, which are calculated by equations 1 to 3.
- Actual total cost per unit of product of first commercial scale ($/ ton, eq. 1, 2 and 3, table 1)
- Errors or cost overrun in estimated costs ($/ton, eq. 4, table 1)

Table 4. 4: Actual total cost and design estimated cost error per ton of PF resin precursor for first commercial scale variables

<table>
<tr><th>Variable name</th><th colspan="2">Solvent pulping process</th><th>Ligning precipitation process</th></tr>
<tr><td>Known technology, (%), [49]</td><td colspan="2">58
Comments:
79 (m$/year) investment in new technologies such as:
- Saccharification unit: uncertainties about the type of vessel that has to be used in commercial scale.
- Solvent recovery unit: uncertainties about the recovery of solvent.
- Lignin precipitation unit: uncertainties about the techniques to achieve the targeted quality of lignin.</td><td>72
Comments:
611000 ($/year) investment in new technologies such as:
- Filter press and dryer units: these technologies have never been used for lignin precipitation process at commercial scale.
- Coagulation unit: this technology has never been used at commercial scale.</td></tr>
<tr><td>Project definition, (%), [49]</td><td colspan="2">90
Comments: 70% of detailed engineering step is completed.</td><td>95
Comments: 80 % of detailed engineering step is completed.</td></tr>
<tr><td rowspan="2">Risk score, (dimensionless)</td><td colspan="2">0.05</td><td>0.02</td></tr>
<tr><td>Scale up risk</td><td>0.02
Comments: relative to the most similar commercial project, the different unit of operations are: 1- Lignin precipitation, 2- Distillation tower, 3- Evaporator, 4- Digestion vessel (in case of type vessel</td><td>0.01
Comments: relative to the most similar commercial project, the different unit of operations are: 1-Filter press, 2- Dryer, 3- Lignin coagulation.</td></tr>
</table>

		there are uncertainties in scale up).	
	Mass integration risk	**0.02** Comments: It is a stand-alone process so it has few impacts on pulp production process such as: - Materials handling system: it has to be adapted to biomass procurement scenarios of the host pulp mill. - Waste water treatment: Uncertainties about the separation process of water and solvent, so this may affect waste water treatment of the mill.	**0** Comments: - It will not affect the pulp production process. - It has no disruptive impact on waste water treatment.
	Energy integration risk	**0.12** Comments: - Steam and electricity productions have to be adapted and optimized according to requirements of the both pulp and solvent pulping processes. - There is no need for a new boiler, only additional costs in using one of the power boilers and electricity consumption have to be considered.	**0.06** Comments: - Lignin precipitation units are easily integrated within the existing energy system. - Additional natural gas need to be fed into one of the power boilers. - It decreases the amount of organics in the black liquor, so energy management need to be adapted.

Optimism bias, (dimensionless)	**0.03**	**0.06**
	Comments: Both technologies do not have high level of optimism bias because: - They became more mature, due to long period of time that has been elapsed in these technologies. - They have a lot of interfaces with energy companies. - They ran a lot of cost estimates. However based on discussions during the interviews, solvent pulping technology providers seem to have less optimism bias than lignin precipitation technology providers.	
Actual total cost per ton of PF resin precursor ($/ton)	**1900** Comments: Each ton of total production includes 38% PF resin precursor,36 % sugar syrup, 23% ethanol and 3% acetic acid.	**1100** Comments: Each ton of total production includes 100 % PF resin precursor.
Errors in estimated costs per ton of PF resin precursor ($/ton)	**200** Comments: Each ton of total production includes 38% PF resin precursor,36 % sugar syrup, 23% ethanol and 3% acetic acid.	**100** Comments: Each ton of total production includes 100 % PF resin precursor.

Table 4-5 presents impacts of cost reduction factors. The main reference of this part is from result of industry partners' interview. This table also contains values of:

- Experience index (b), which is calculated based on 4 identified factors of cost reduction and eq. 5 (in which C_0 is cost per unit of production for first commercial scale (eq.1) and CUM is cumulative production in nth installation)
- Progress ratios (PR, eq. 7)

Table 4. 5: Emerging biorefiney independent factors of cost reduction, progress ratio estimate.

Variable name	Solvent pulping	Lignin precipitation
Effects of economies-of-scale on total capital cost reduction per ton of product, [37]	Around 60% reduction in capital cost per ton of PF resin production.	There is no effect of economies of scale for this process. The reason is that this process is highly resticted to black liqour production from Kraft process. Lignin precipitation process production capacity increases if the Kraft process' s capacity production increases.
Effects of economies-of-scale on fixed oprating cost reduction per ton of product	90% reduction in fixed operating cost per ton of PF resin production.	There is no effect of economies of scale for this process. The reason is that this process is highly resticted to black liqour production from Kraft process. Lignin precipitation process production capacity increases if the Kraft process' s capacity production increases.
Effects of process operation optimization	**Labor costs:** Around 20% reduction in operating labor cost (fewer people; from 57 to 52) per ton of PF resin production. This is due to improved experiences in operations and maintenance and better equipment selection. **Energy costs:** Around 15% reduction in energy costs. This is due to process improvements and	**Labor costs:** Around 60% reduction in operating labor cost (fewer people; from 7 to 3) per ton of PF resin production. This process is an integrated process to Kraft pulp mills so the required labors can be shared between to processes. Few persons may be needed for quality control. **Energy and feedstock costs:** 40% reduction in energy and chemical

	energy efficiency. **Feedstock costs:** 45% and 25% reduction in enzyme and biomass costs by 2020 respectively. This is due to optimization in production yield and recycling of enzymes and optimization in harvesting and transportation of woods [81]. **Maintenance cost:** Around 25% reduction in maintenance cost due to learning.	costs. This is due to process improvements, energy efficiency and less CO_2 consumption. **Maintenance cost: A**round 25% reduction in maintenance cost due to learning.
Effects of process design optimization and less conservatism	Design uncertainties could add up to 20% to equipment costs for the first plant. This cost will be reduced for the subsequent plants. The uncertainties are mostly in how certain processes will scale up and how much potential there is, for process improvement with experience.	Better integration of their process into pulp processes can result in reduction of the capital cost. However in this study this impact was not considered due to lack of available information about this improvement.
Effect of process improvement with incremental new technology additions post-implementation	10% more energy saving by converting the process from batch to continuous process.	100% reduction in CO_2 cost by a replacement for acidification agent CO_2 (e.g. using H_2SO_4).
b, (dimensionless)	-0.37	-0.05
Progress ratio, (%)	77	96

It is important to mention that there is another potential for capital cost reduction. This potential is about capital cost's contingency. This contingency is only considered for first commercial scale, then in post commercial scale, capital cost per ton of product will be reduced. According to results of industry partners'' interview this contingency for case studies is:

- Solvent pulping process: 15%
- Lignin precipitation process: 20%.

Figures 4-6 and 4-7 illustrate cost overrun for first commercial scales and cost development at commercial scales of the case studies.

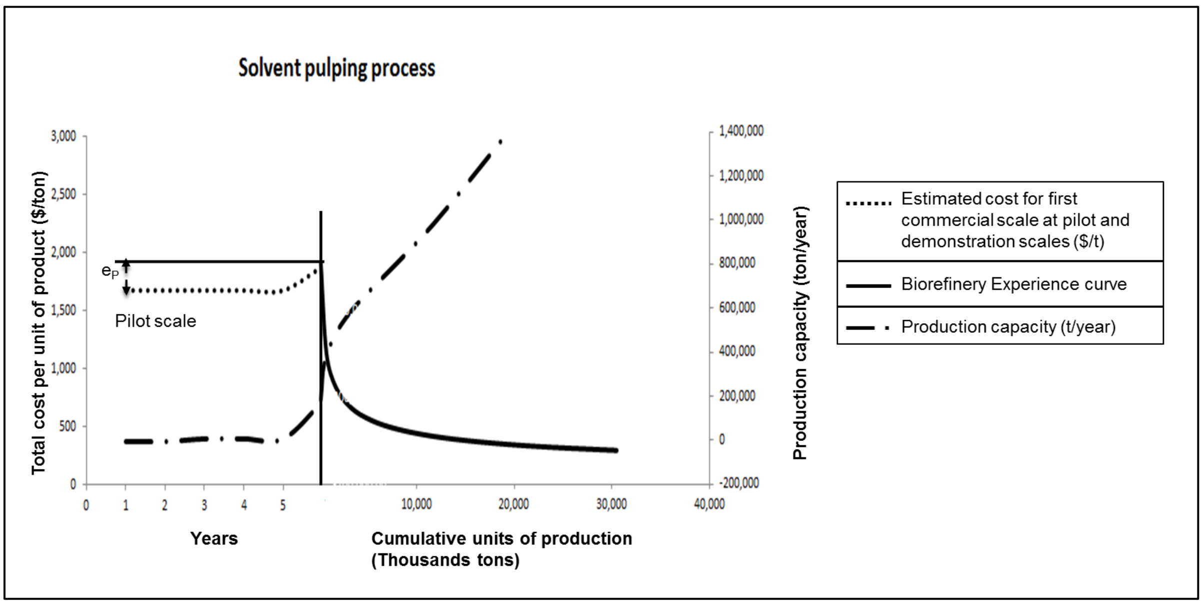


Figure 4. 6: Solvent pulping process experience curve

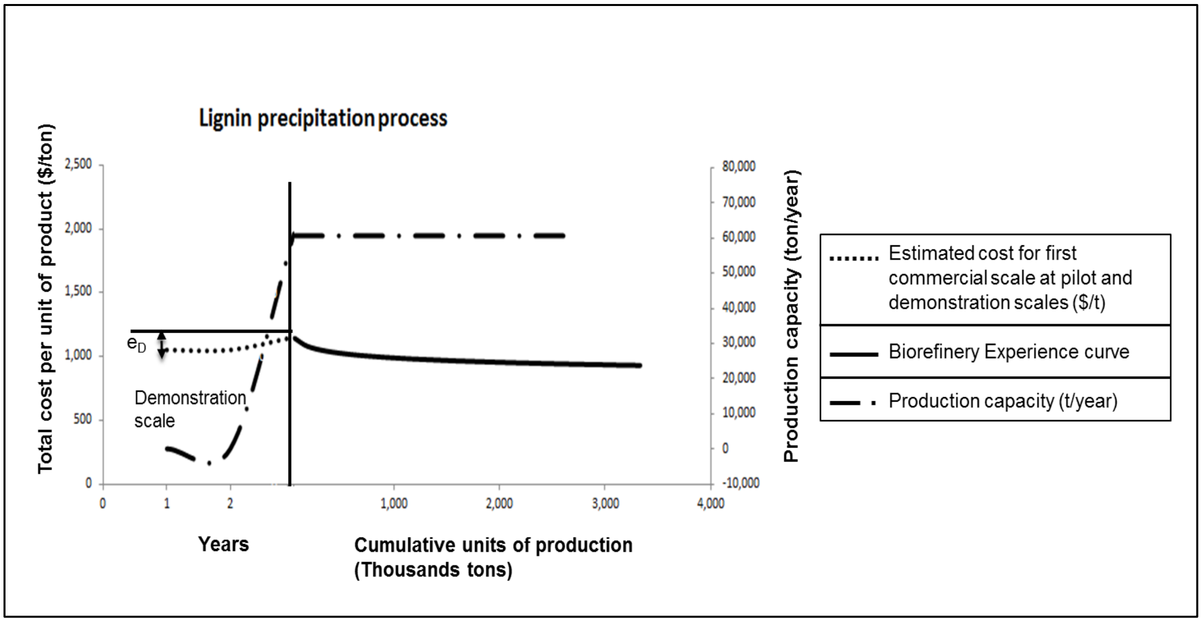


Figure 4. 7: Lignin precipitation process experience curve

According to figures 4-6 and 4-7 both case studies showed cost overrun for first commercial scale:

- Solvent pulping process have cost overrun of 200 $ per ton PF resin precursor over the design estimated cost (1200 $/ton).
- Lignin precipitation process have cost overrun of 100 $ per ton PF resin precursor over the design estimated cost (1900 $/ton).

According to this the solvent pulping process is more costly than lignin precipitation process for first commercial scale. As a result in a short-term vision of business plan lignin precipitation with less total cost per ton of PF resin precursor in first commercial scale is more promising. In long term vision when market and demand of lignin products will be developed solvent pulping will be more beneficial. The reason is that it has more potential for cost reduction (progress ratio of 77%) and more quantity and better quality of lignin.

4.1.3 Conclusions

In this chapter a new model of experience curve underlying the fundamental factors of cost estimation before and after commercialization of unproven biorefineries is discussed. The main identified factors of cost underestimation in pre-commercial scale are:

2. New technology
3. Appreciation for and level of design engineering
4. Appreciation for risk associated with integration and scale up
5. Optimism bias of the technology and project developers.

The main identified factors of cost reduction in post commercial are:

1. Economies-of-scale
2. Process operation optimization due to learning
3. Process design optimization and less conservatism in design due to learning
4. Process improvement with new technology additions post-implementation.

The important aspect of this model is that these 8 factors are empirical. On that account each of them and also the model can be debated and expressed differently. The results of the case study application of the experience curve model show that both of the lignin-based case studies underestimated the cost of fist commercial scale. This is mainly because of new technology, appreciation for and level of design engineering, appreciation for risk associated with integration and scale up and optimism bias of the technology and project developers. At commercial scale factors of cost reduction (economies-of-scale, process operation optimization due to learning, process design optimization and less conservatism in design due to learning, and process improvement with new technology additions post-implementation) resulted in cost decrease of the case studies.

CHAPTER 5: GENERAL DISCUSSION

Financial difficulties of P&P mills in North America decreased their business competitiveness. This is due to decreasing demand for traditional P&P products, increasing energy prices and increasing competition from countries where labor and production costs are lower. A business transformation by integration of biorefinery processes is required. The reason is that biorefinery can diversify products and increase revenues. In this context since most of biorefinery technologies are emerging and are not commercially developed, they are associated with uncertainties. Uncertainties in costs of biorefineries before and after commercialization (especially capital costs) decrease the quality of the planning for commercialization. On the other hand different stages of development (laboratory, pilot or demonstration scale) of dissimilar biorefineries, makes the effect of cost misestimating more challenging for forest product industry.

Furthermore information about commercial cost trend of biorefinery technologies is critical for forest product industry to better compare competitiveness of candidate technologies.

Therefore objective of this work was to propose a model of experience cuvre. This can address cost uncertainties of emerging biorefinery technologies before and after commercialization. This model is applied to dissimilar lignin-based biorefinery case studies to demonstrate its application in a practical way.

5.1 Proposed model of experience curve for emerging biorefinery technologies

In the proposed model of experience curve factors of cost misestimating are identified and used: 1- new technology, 2- appreciation for and level of design engineering, 3- appreciation for risk associated with integration and scale up, and 4- optimism bias of the technology and project developers. A model that can underline all these factors inspired by IPA model (discussed in 2.2.3, [49]) was proposed. This model analyzes the estimated cost of first commercial scale and calculates the actual total cost per unit of product of emerging bioreinery technologies. The result of this section is used as a starting point for the second part of proposed model of experience curve, where experience curves happen.

On the second part of this model four main factors for cost reduction are identified and used: 1- economies-of-scale, 2- process operation optimization due to learning, 3- process design optimization and less conservatism in design due to learning, and 4- process improvement with new technology additions post-implementation. These factors as the most important drivers of cost reduction at commercial scales enable the development of experience curve for emerging biorefineries that do not have any historical cost data at commercial scale. In this work the traditional experience curve (discussed in 2.3.3) equation is used. However for the case of emerging biorefineries the variable “b” of this equation is predicted based on four mentioned factors of cost reduction.

5.2 Results of application of the experience curve model for the case studies

The proposed model of experience curve is applied to lignin-based biorefinery case studies. The results of this application show that new technologies, lack of project definition, integration risks and optimism bias effect the accuracy of the early design cost estimation, especially capital costs.

On the right side of the experience curve model, both applied case studies show cost reduction as it was expected for cost curves at commercial scales. All four identified factors of cost reduction (economies-of-scale, process operation optimization due to learning, process design optimization and less conservatism in design due to learning, and process improvement with new technology additions post-implementation) resulted in reduction of capital and/or operating costs. The results from this section provide valuable information for better comparison of the biorefinery candidates in case of their competitiveness.

In this research the two case studies show different potential for commercialization and commercial scales costs. Lignin precipitation with less cost of first commercial scale but less potential for cost reduction in commercial scale is more suitable for short-term vision of business transformation. On the other hand solvent pulping with higher cost for commercialization but more potential for cost reduction in future, better quality of lignin and more quantity of lignin is more promising for long-term vision.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Contributions to the body of knowledge

A model to analyze the accuracy of the estimated cost for first commercial scale of emerging biorefinery technologies

- Including the most important factors of cost underestimation compared to other identified models, which mostly focus on new technology and project definition.
- A systematic comparison of emerging biorefineries with different stage of development (laboratory, pilot and demonstration scales) in case of commercialization cost
- The uncertainty in early design cost estimation is mitigated due to systematically addressing the effects of cost underestimation
- Potential for being integrated with techno-economic methodologies and providing information/criteria for decision making techniques such as MCDM framework

A new experience curve model to predict cost development of emerging biorefinery technologies

- The model considers the most important cost reduction parameters and provides future cost trends at commercial scales of undeveloped biorefineries
- Potential for being integrated with techno-economic methodologies and providing information/criteria for decision making techniques such as MCDM framework

Introducing the proposed model of experience curve for lignin based biorefinery case studies

- This model claims to be effective for industrial projects and case studies, due to providing information for a more systematic comparison of case studies in short-term and long-term business visions

To sum up, the model proposed in this thesis provides actual cost of first commercial scales and cost developments of emerging biorefinery technologies such as lignin-based biorefineries. Ultimately, the model is intended to be used to analyze and compare cost information of biorefinery strategies before and after commercialization. To the best of our knowledge, no literature focusing on such issues in the context of biorefinery has been found.

6.2 Future work

Experience curve model results as criteria for decision-making

Results of application of experience curve model to case studies provide valuable information about cost of emerging biorefineries at pre and post commercial scales. Defining some decision-making criteria based on these information for decision-makings techniques such as MCDM could validate the importance of this provided information.

Emerging biorefinery case studies

The aim of choosing lignin-based biorefinery case studies as emerging biorefineris for experience curve model was to practically present the application of this model. Utilization of other emerging biorefinery case studies could potentially enhance further the understanding of the proposed model.

Experience curve model validation

By comparing cost estimation error of projects with the cost estimation error from the original estimated. This in turn results to validate the experience curve model.

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APPENDICES

APPENDIX A – The adapted experience curve model for emerging biorefineries - Part I: The model

The adapted experience curve model for emerging biorefineries - Part I: The model

In the context of biorefinery integration into a pulp and paper mill, costs comparison of emerging biorefinery strategies before and after commercialization is challenging. Therefore, it is crucial to propose a well-defined strategy to address this problem to some extent. This study proposed an experience curve model adapted for biorefineries. This model evaluates the required expenditures for a first commercial scale plant and predicts future costs. In order to achieve the goal of this paper, the authors analyze unproven biorefineries from two different aspects; 1- cost misestimating at pre-commercial scales, and 2- examining their experience curves. Then factors of cost over-run in pre-commercial scale and cost reduction in post-commercial scale are identified. Thus to systematically address these factors, a suitable model inspired by experience curve approach is proposed. The main factors for pre-commercial scale are: new technology, appreciation for and level of design engineering, etc. The main identified factors for post-commercial scales are: economies-of-scale, process operation optimization due to learning, etc. The targeted experience curve model can provide beneficial information about the cost evaluation in planning and decision-making in the implementation and commercialization of biorefinery technologies. Application of this model for biorefinery case studies has been carried out in part two of this study.

As an Introduction Pulp and paper industries in North America continue to struggle with financial difficulties. This is mainly due to increasingly lower demands for traditional pulp and paper products, increasing energy prices and increased competition from low-cost countries. In this condition to remain competitive, business transformation is required, that can be initialized by integration of biorefinery processes into current mills. In case of unproven biorefineries this is a challenging task due to the associated uncertainties. The main focus of this study is on uncertainties in first implementation costs and long-term competitiveness. Misestimating of biorefinery costs for first commercial scale may result in failure of the project. On the other in order for a pulp mill to make well-informed decisions, information about long-term competitiveness of biorefinery candidates is also necessary.

Therefore a model that can address previously stated estimates and forecasting costs is of primary importance.

Cost estimation of new technologies prior to commercial scaling

For the last four or five decades, accuracy of cost estimate has been a major concern for investors of new technologies. In 1965, Hackney provided a definition checklist to identify required contingency for the estimated capital costs. This checklist contained six principal definition categories: general project basis, process design, site information, engineering design, detailed design and field performance. Twenty years later, he validated the definition checklist by comparing cost overrun of projects with the considered contingency.

The importance of Hackney's general work was captured by the RAND Corporation. They developed a cost growth model to analyze the cost estimate of non-commercial technologies. This model was based on analyzing data sets from forty-four energy technologies and chemical process plants in North America. Several assumptions were made to explain the reasons of inaccurate cost estimates. Afterwards, by running a multi-variant regression, they identified the main reasons such as: PCTNEW, IMPURITIES, COMPLEXITY, INCLUSIVENESS and PROJECT DEFINITION. The RAND model has been also applied to techno-economic studies in biorefineries,. However in these works, the authors did not take into consideration that this model was defined prior to commercial development of biorefinery technologies. This in turn introduces some uncertainties into the application of this model. Moreover the RAND model contains some factors that are not important for biorefinery technologies or already are considered in their cost estimates (e.g. impurities and inclusiveness).

Steven et al. developed a mathematical model to predict the accuracy of early cost estimation of construction projects. This model takes into account factor analysis and multivariate regression of survey. They proposed forty-five reasons for cost misestimating including internal and external factors of poor cost estimation. It is important to mention that the main focus of this study is to elaborate more on the effects of internal factors rather than external factors. Internal factors are those, which are easily controllable, and cost estimators can consider them in cost estimations to avoid misestimating such as percentage of new technology, level of project definition, etc. On the other hand, external factors such as inflation, strikes and etc. are those, which are not under control. Five important factors out of those forty-five factors were identified by the run regression. These factors in order of significance are: 1- basic process design, 2- team experience and cost information, 3- time allowed to prepare the estimate, 4- site requirement, 5-

bidding and labor climate. The four first factors can also be considered in “level of project definition” factor as it is addressed in engineering design steps. Moreover the fifth factor is an external factor of cost overrun, which is not controllable; for that reason the cost estimators are not responsible for its prediction.

In 2005, the Independent project analysis Inc. website described project contingency as a variable of percentage of new technology and level of project definition. This is particularly important in the context of biorefineries that are associated with undeveloped technologies. The IPA model was developed based on a data set from various projects to analyze their estimated capital costs. This model showed that none of the projects are overestimating the cost of first commercial scale. In fact many of them are below 60% of the actual cost.

Among the reviewed models, the RAND model and the IPA model have more focused on assessing internal factors of poor cost estimation and not on external factors. The IPA model was developed more recently (in 2005) than RAND model, in fact at the same time that several biorefinery technologies were being developed. Thus, using these models we can account for the likely cost underestimation prior to commercial scale. However for biorefineries, these models should be augmented in a practical way considering important factors such as optimism bias of technology and project developers.

Cost improvement of energy technologies at commercial scale and experience curves

The experience curve approach was developed to forecast the cost of technologies based on pre-existing data. This approach is based on the learning curve, which in turn, indicates the cost of labor in producing a unit of product. The experience curve gives a parameter called "progress ratio”. A progress ratio of 80% means that when cumulative production doubles, production costs per unit of product lowers by 20%. The curve is expressed by eq. 1, 2 and 3. The production cost dynamics is a function of cumulative production and technological learning in this method.

$$C_n = C_0 * \left(\frac{CUM_n}{CUM_0}\right)^b \tag{E-1}$$

$$b = \frac{\mathrm{Ln}\frac{C_n}{C_0}}{\mathrm{Ln}\frac{CUM_n}{CUM_0}} \tag{E-2}$$

$$\text{Progress ratio} = 2^b \tag{E-3}$$

C_n: the cost per unit as a function of output

C_0: the cost of the first unit produced

CUM: the cumulative production over time

b: the experience index

A detailed review of energy technologies' experience curves was carried at New Energy Externalities Developments for Sustainability (NEEDS) project. This review mainly focused on technologies that produce electricity (e.g. wind, water, solar, nuclear, etc.). The aim of this study was to develop a framework for future cost of energy technologies. To do so, they compared three different approaches: 1- experience curve, 2- a bottom-up analysis and 3- expert assessments. The experience curve model was already discussed above. Bottom-up analysis is not a methodological approach. It quantifies the total improvement potential, and ultimately minimum cost level of a technology to its maximum cost. Expert assessments approach is based on technology experts' judgments. This method is used to evaluate the predicted cost development paths; for that reason it was suggested to be combined with two other approaches. All the three methods exhibit cost reductions in commercial scales of energy technologies with the exception of nuclear technology. In nuclear technology the experience curve showed cost increment which is mainly due to safety and environmental regulations, whereas the bottom-up technique showed a cost stabilization. However, for pioneer technologies such as forest biorefineries the experience curve is more suitable than the bottom-up approach. This is due to the fact that experience curve approach starts from the highest costs to the least possible cost, whereas the bottom-up approach works in the opposite way. The report also suggested using a range of progress ratios for experience curves instead of one fixed number to underline uncertainties in cost forecasting.

In 2009 Bake et al. showed the reasons for cost reductions in Brazilian corn ethanol production based on historical cost data. They also studied the possibility of dividing an experience curve of total production cost into its main components (e.g. feedstock and industrial costs). Separating experience curves for each cost component would give better insight into the drivers of cost reduction and also would better predict future cost trends. At the same time Hettinga et al. performed the same approach of experience curve on U.S. ethanol. The main goal of this study was to find the main reasons for cost reduction in the past such as effects of economies of scale, learning in the operation and maintenance, etc. They also use information from the experience curve to evaluate its long-term competitiveness. It is worth mentioning that this approach of experience curve to predict the future costs from historical data is not applicable for biorefineries that are not yet commercialized.

In addition to the previous studies, the National Renewable Energy Laboratory (NREL) carried out another approach inspired by experience curve to predict future costs of non-commercial technologies such as lignocellulosic ethanol production. In 2002 they analyzed the effect of economies of scale on the minimum price of ethanol from lignocellulosic biomass in two parts: feedstock cost and non-feedstock cost. The effect of economies of scale on non-feedstock costs resulted in a lower minimum price of ethanol as it is usually expected. However for feedstock costs, the effect behaved in the opposite manner, which is due to feedstock-specific challenges such as transportation costs. Later in 2011 NREL executed a more comprehensive approach than previously done. The later work predicts cost curves of feedstock, enzymes and conversion to depict the future minimum-selling price of ethanol. Although their assessment is done particularly for the case of lignocellulosic ethanol, a systematic methodological approach is missing.

The experience curve methodology has been applied in many cases historically, (e.g. technology area and also biorefinery). This methodology provides valuable information about costs, time and the cumulative production by which technologies can achieve market competitiveness. The progress ratio in this approach has been evaluated on ad hoc basis. Hence a model should be proposed that addresses this deficiency. This model directly takes into account the effect of key factors which influence the estimated cost of both first commercial scale plant and the future biorefinery costs.

The objectives of this study are:

1. To identify and distinguish between fundamental factors affecting pre-commercial and post commercial scales' cost estimates.
2. To propose a new model suitable for emerging biorefineries, inspired by the experience curve. This model will enable us to compare the long-term estimated costs both for pre-commercial and post commercial scales.

The overall methodology to achieve the goal of this study is shown in fig. 1:

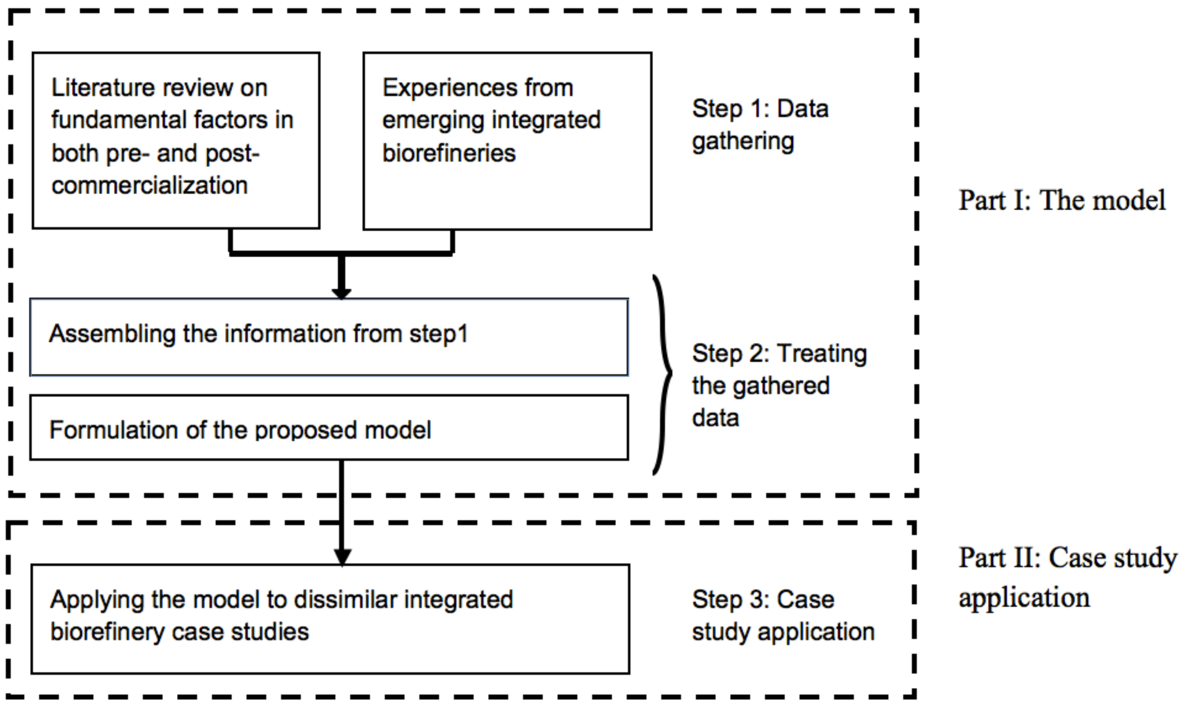


Fig. 1- Schematic representation of the methodology

In the first step we consider two sources of information:

1. Analysis of literatures on both factors before (cost underestimation) and after commercialization (cost reduction).
2. Experiences from some biorefinery cases being implemented in retrofit of forest product companies with emphasize on the factors before and after commercialization.

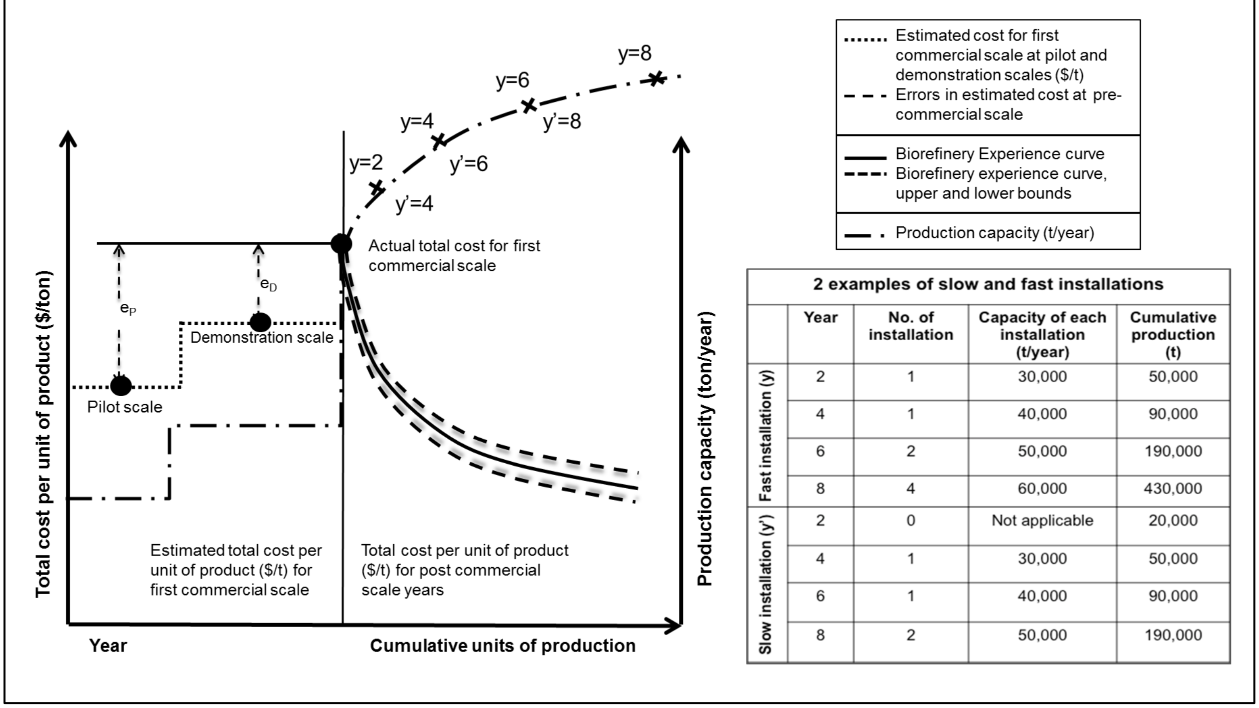
In step two, this information was assembled to obtain a model that captures the main factors to predict future biorefinery costs.

However to appreciate the empiricism of the model it should be applied to dissimilar biorefinery case studies (this will be the main focus of part two of this paper).

Figures 2 and 3 show the list of main identified parameters and the new experience curve model respectively.

Left side of the experience curve model: Factors of cost underestimation at pre-commercial scales:	**Right side of the experience curve model: Factors of cost reduction commercial scales:**
a. New technology b. Appreciation for and level of design engineering c. Appreciation for risk associated with integration and scale-up d. Optimism bias of the technology and project developers	a. Economies-of-scale b. Process operation optimization due to learning c. Process design optimization and less conservatism in design due to learning d. Process improvement with incremental new technology additions post-implementation

Fig. 2- Fundamental factors of cost underestimation and cost reduction before and after commercialization



2 examples of slow and fast installations				
	Year	**No. of installation**	**Capacity of each installation (t/year)**	**Cumulative production (t)**
Fast installation (y)	2	1	30,000	50,000
	4	1	40,000	90,000
	6	2	50,000	190,000
	8	4	60,000	430,000
Slow installation (y')	2	0	Not applicable	20,000
	4	1	30,000	50,000
	6	1	40,000	90,000
	8	2	50,000	190,000

Fig. 3- The proposed model of biorefinery experience curve. e_p: error in estimation of total cost of first commercial scale when a technology is in pilot scale. e_D: error in estimation of total cost of first commercial scale when a technology is in demonstration scale. y: year.

Left side of the fig. 3 presents the results of analyzing total cost estimation of first commercial scale. It indicates that there are four factors that contribute to cost underestimation of the first commercial scale:

- New technology: Technologies that are not implemented in commercial scale and are associated with various uncertainties.
- Appreciation for and level of design engineering: Definition level of a project according to the engineering process design steps (e.g. prefeasibility, feasibility, definition and/or detailed engineering and construction).
- Appreciation for risk associated with integration and scale-up:
    - Scale up risk refers to comparison of the current existing scale and the targeted scale at commercialization. Also a plant with a large number of units (“complexity”) will have a higher risk level.
    - Integration risks are related to impact core business, e.g. materials handling, steam and power consumption and generated waste.
- Optimism bias of the technology developer and project developer: A bias related to the personality, knowledge and experience of the technology and project developers.

Right side of the fig. 3 predicts cost development paths following to the first commercial scale. Once a technology is commercialized, the project costs will decrease every time this technology is implemented (e.g. construction of a new biorefinery or add-on at an existing facility). The trend in cost reduction is continuous especially for commodity product manufacturing for many years. In order to underline the empirical nature and thus uncertainty of progress ratio value for a given technology, the upper and lower bounds are suggested (dashed lines). Based on experience, cost reduction after commercial implementation occurs mainly due to the following reasons:

- Economies-of-scale: The annual capital cost and fixed operating cost per unit of production decrease by increasing process capacity. These depend on the principal of design and operation to different extents.
- Process operation optimization due to learning: The operating cost of new processes decrease on a unit production basis. This contains key variable cost components such as raw material and maintenance costs.
- Process design optimization and less conservatism in design due to learning: Designers over-compensate for the first commercial scale to mitigate technology risk (i.e. the lowest possible cost is of secondary importance). Following the first commercial implementation, a more aggressive design approach can be taken due to learning and experience from previous implementations.
- Process improvement with new technology additions post-implementation: Innovations with incremental improvement are typically considered after the first implementation. This results in lower capital and/or operating costs. They are implemented in successive projects to mitigate risk and as new ideas emerge based on operating experience.

The model is associated with number of years and process throughput. It underlines the future improvement and progress of technologies in the context of fast or slow installations (two examples of slow and fast installations are given in fig.3).

Cost accuracy analysis model for biorefineries

A model is proposed that estimates actual total cost per unit of product for first commercial scale of emerging biorefineries (eq. (4)). This model serves as the starting point of the experience curve. It is expresses by the two following equations: eq. (5) and eq. (6).

$$\begin{aligned}&Actual\ total\ cost\ per\ unit\ of\ product\\&=\frac{Actual\ annual\ capital\ expenditure\ \left(eq.(2)\right)+Actual\ annual\ operating\ cost\ (eq.(3))}{Estimated\ annual\ production\ capacity}\end{aligned} \quad \text{(E-4)}$$

$$Actual\ annual\ capital\ expenditure = \frac{Estimated\ annual\ capital\ expenditure}{a * Known\ technology + b * Project\ definition} * \frac{1}{(1 - Risks'score) * (1 - Optimism\ bias)} \quad \text{(E-5)}$$

$$Actual\ annual\ Operating\ cost\ = \frac{Estimated\ annual\ operating\ cost}{(1 - Risks'score) * (1 - Optimism\ bias)} \quad \text{(E-6)}$$

Cost estimation error in pre-commercial scale (e.g. pilot or demonstration) is calculated by eq. (7). Each parameter of these equations is defined in table 1. Ranges of values for parameters are defined using a relative scale by several questions that can be asked during the industry partners' interviews.

$$e_P\ or\ e_D = Actual\ total\ cost\ per\ unit\ of\ product\ (eq.(1)) - \frac{Estimated\ annual\ capital\ expenditure + Estimated\ annual\ operating\ cost}{Estimated\ annual\ production\ capacity\ for\ first\ commercial\ scale} \quad \text{(E-7)}$$

Table 1 – Actual total cost per unit of product for first commrcial scale' and e_P or e_D equations' variables

Variable name	Model	Range of value	Parameter estimate
Estimated annual production capacity, ($/year), eq. (4) & (7)	According to the model proposed by "plant design and economics for chemical engineers".	0 to total process production capacity	n.a
Estimated	According to the model proposed by "plant design and	0 to total	n.a

<table>
<tr><td>annual capital expenditure, ($/year), eq. (5) & (7)</td><td colspan="2">economics for chemical engineers”.</td><td>process capital cost</td><td></td></tr>
<tr><td>Known technology, (%), eq. (5)</td><td colspan="2">$Known\ technology = 1 - \frac{Investment\ in\ new\ technology}{Total\ project\ investment}$</td><td>0 to 100</td><td>a=0.5</td></tr>
<tr><td>Project definition, (%), eq. (5)</td><td colspan="2">According to percentage of engineering design a technology completed [12]. E.g. for prefeasibility: 40, feasibility: 60, engineering for definition: 80 and detailed engineering: 100.</td><td>40 to 100</td><td>b= 0.5</td></tr>
<tr><td rowspan="2">Risk score, (dimentionless), eq. (5) & (6)</td><td colspan="2">$Risks'\ score = 0.5 * Scale\ up\ risk + 0.25 * Mass\ integration\ risk + 0.25 * Energy\ integration\ risk$</td><td>0 to 0.08</td><td>n.a</td></tr>
<tr><td>Scale up risk</td><td>Judgment based, using a relative scale.
E.g. relative to the most similar commercial project:

3. If numbers of different unit of operation is 2 or less than 2, the risk score is 0.
4. If it is between 2 and 10, for each number of unit more than 2, value of 0.01 should be added to 0.
However numbers of different units should not be more than 11, otherwise it shows the technology is prone to have a high risk at the time of implementation.</td><td>0 to 0.09</td><td>n.a</td></tr>
</table>

	Mass integratio n risk	Judgment based, using a relative scale. E.g. if there is a linkage between a new process and a pulp process, that can potentially result in negative impact in the core business, the risk score is 0.02. However this risk is eliminated through in-situ testing.	0 or 0.02	n.a
	Energy integratio n risk	Judgment based, using a relative scale. E.g. relative to energy system of a targeted pulp mill: 6. If the energy requirement of new process is equal or less than the existing energy system, the risk score is 0. 3. If it marginally exceeds the design capacity of the turbines or boilers, the risk score is 0.06. 4. If it significantly exceeds the design capacity of the turbines and boilers, the risk score is 0.16. However this risk is eliminated through capital expenditure.	0, 0.06 or 0.12	n.a
Optimism bias, (dimentionless), eq. (5) & (6)	Judgment based, using a relative scale. E.g. relative to how each technology developer over-value their technology, how they believe optimism bias effects cost estimates prior to commercialization, how they address this bias relative to your technology, etc.		0 to 0.08	n.a
Estimated annual operating	According to the model proposed by “plant design and economics for chemical engineers”.		0 to total process operating	n.a

cost, ($/year), eq. (5) & (7)		cost	

n.a.-not applicable

Unproven biorefinery technologies do not allow to extrapolate for future cost curves due to lack of historical data. Therefore this study suggests:

- Equation 4 can be used to calculate the actual total cost per unit of product for first commercial scale.

- Cost reduction factors, eq. 1 and eq. 2 can be used to estimate cost reduction of nth plant and progress ratios. Each of these factors is defined in table 2.

Table 2 – The main drivers of cost reduction at commercial scale

Variable name	Model	Range of value
Economies-of-scale, (%)	Fixed operating cost: case-by-case assessment	0 to 100
	Capital cost: $C = C_{ref}\left(\frac{M}{M_{ref}}\right)^{\alpha}\left(\frac{i}{i_{ref}}\right)$	0 to 100
Process operation optimization due to learning, (%)	Case-by-case assessment related to cost reduction rate of following sections: • Labor cost • Raw material cost • Maintenance cost	0 to 100
Process design optimization and less conservatism in design due to learning, (%)	Case-by-case assessment related primarily to: • Uncertainty in design parameters. • Complexity of the overall process.	0 to 100
Process improvement with new technology additions	Case-by-case assessment based on identified incremental new technology changes.	0 to 100

post-implementation, (%)		

C is related to cost of new equipment,

ref belongs to reference of related values

M indicates the capacity of new equipment

α is the exponent of the capacity

i are used as cost index.

Implementing the forest biorefinery at a pulp mill requires some critical consideration of uncertainties in the cost of commercialization and long-term costs. The main objective of this study was to propose a model of experience curve for emerging biorefineries. This model included the fundamental factors of cost estimation before and after commercialization. In order to achieve this goal, literatures related to previously stated factors were reviewed. Then the critical information from this step was assembled to provide principals of the targeted model. Therefore four equations were proposed (eq. 4 to 7) to calculate actual total cost per unit of product and cost overrun of first commercial scale. Once actual total cost is calculated, it is used as the main input for the experience curve model. In addition to this the progress ratio is defined based on the effects of the cost reduction factors.

Finally the results of this model can be utilized by the forestry sector in evaluating and decision making of emerging biorefinery technologies. The important aspect from this study is that the factors considered are based on experience and what authors (S.M and P.S) believed to be rational. Therefore each of these factors and also the model maybe debated and expressed differently. The validation of this model by some biorefinery case studies has been taken into account in part two of this paper.

APPENDIX B – The adapted experience curve model for lignin-based biorefineries - Part II: Case studie

The adapted experience curve model for lignin-based biorefineries - Part II: Case studies

There are several uncertainties associated with converting a Kraft pulp mill into an integrated forest products biorefinery. Uncertainties in costs of unproven biorefineries affect commercialization and long-term competitiveness. Part one of this paper proposes an experience curve model to address these cost uncertainties. Therefore this study aims to illustrate the application of this model for lignin-based biorefinery case studies. Main steps to accomplish this objective were: 1- Selecting two lignin-based biorefinery cases to be integrated into a Kraft pulp mill, 2- large block analysis and experience curve factors assessment (e.g. new technology, level of project definition, etc.), 3- executing the experience curve model, and 4- interpreting the results. Two emerging biorefinery case studies were identified: lignin precipitation and solvent pulping processes. Results showed that both case studies underestimate the cost for first commercial scale; solvent pulping process by cost overrun of 200 ($ per ton of phenol-formaldehyde (PF) resin precursor) and lignin precipitation process by cost overrun of 100 ($ per ton of PF resin precursor) over the design cost estimates. In commercial scales solvent pulping showed progress ratio of 77% and lignin precipitation progress ratio of 96%. Accordingly in short term vision of a business plan, lignin precipitation process with less cost per ton of PF resin precursor is more promising. On the contrary, solvent pulping process can better serve the long-term business strategy when demand and market of lignin products are developed. This is mainly due to some parameters such as: more production, better lignin quality and less future cost per ton of PF resin precursor. Finally, the information from this work can be used by forestry sectors to evaluate and compare unproven lignin-based biorefinery technologies that are in different stages of development.

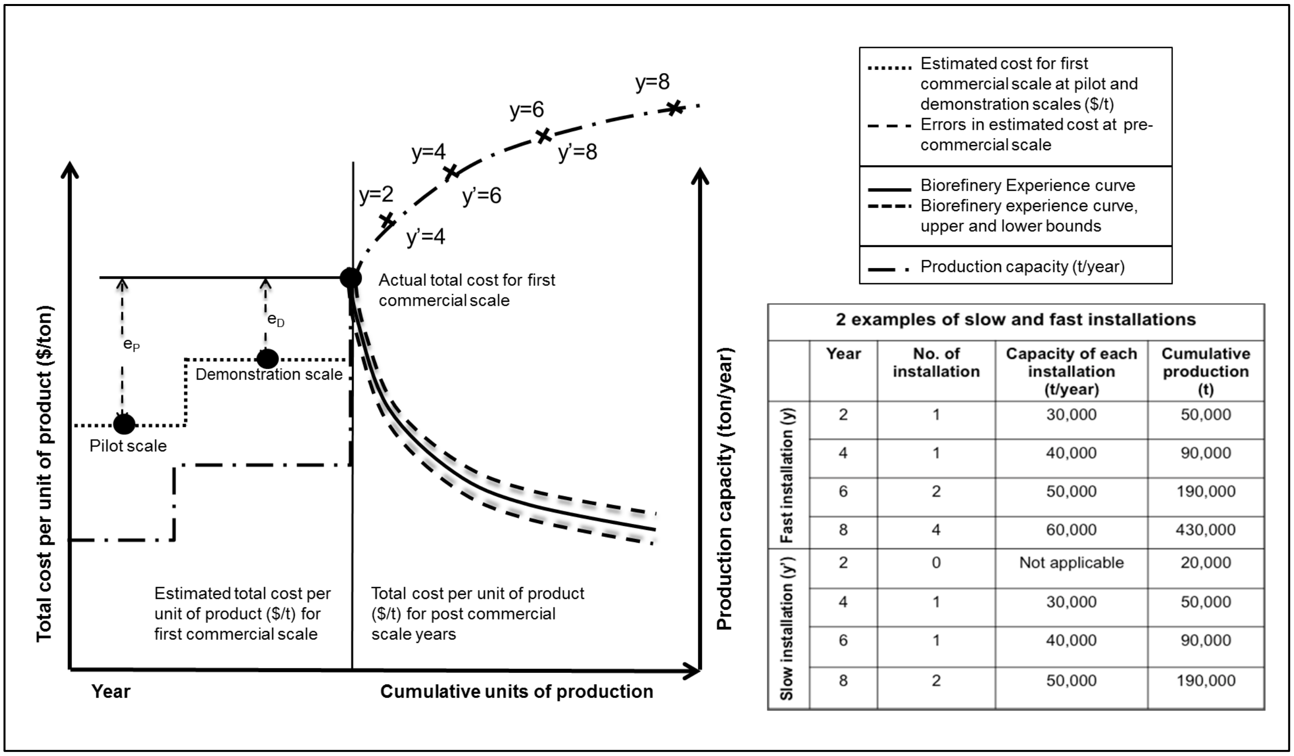
Canadian Kraft pulp mills are increasingly facing competition from other low-cost overseas producers. This has resulted in shut down of many pulp mills over the recent years. Therefore, there is a need to diversify products portfolio and revenue sources. This can be accomplished by biorefinery integration into Kraft pulp mills. There are some uncertainties associated with unproven biorefinery integration such as: first implimentation costs and long term competetiveness. These factors have to be taken into account in integration process.

There have been some attempts to model the cost growth of first commercial scale by RAND corporation and independent project analysis Inc. (IPA). The downside of RAND model is that it is developed prior to the commercial development of biorefinery technologies. Another downside of this model is that it is associated with some factors that are not important for the case of biorefineries (e.g. impurities and inclusiveness). In addition to RAND, IPA model analyzes capital cost estimate of various technologies as a variable of percentage of new technology and level of project definition. This model should be augmented by adding some additional factors such as appreciation for risk associated with integration and scale-up, and optimism bias of the technology and project developers.

Classical experience curve models predict cost development of technologies from commercial historical data. Therefore, they are not applicable for the case of biorefineries that are not yet commercially approved. National Renewable Energy Laboratory (NREL) carried out another approach for unproven biorefineries. They assessed the past successes of a project and targeted some progresses for future to forecast the cost improvement paths. Their prediction for cost reductions in enzyme, feedstock and conversion costs were about 100%, 25% and 75% respectively. A methodological approach that can be applied to all emerging biorefineries is missing nevertheless.

Part one of this paper proposes an experience curve model that focuses on cost uncertainties and comparison of undeveloped biorefineries. The next step is to verify this model by dissimilar biorefinery case studies.

Figure 1 and table 1 present the experience curve model and its main factors from part one of this paper.



	Year	No. of installation	Capacity of each installation (t/year)	Cumulative production (t)
Fast installation (y)	2	1	30,000	50,000
	4	1	40,000	90,000
	6	2	50,000	190,000
	8	4	60,000	430,000
Slow installation (y')	2	0	Not applicable	20,000
	4	1	30,000	50,000
	6	1	40,000	90,000
	8	2	50,000	190,000

Fig. 1- The proposed model of biorefinery experience curve. e_P: error in estimation of total cost of first commercial scale when a technology is in pilot scale, e_D: error in estimation of total cost of first commercial scale when a technology is in demonstration scale, y: year

Table 1 – Factors of experience curve model for emerging biorefinery technologies.

Variable name	Model	Range of value
Known technology, (%), eq. (2)	$\text{Known technology} = 1 - \frac{\text{Investment in new technology}}{\text{Total project investment}}$	0 to 100
Project definition, (%), eq. (2)	According to percentage of engineering design a technology completed [3]. E.g. for prefeasibility: 40, feasibility: 60, engineering for definition: 80, detailed engineering: 100.	40 to 100
Risk score,		0 to 0.08

(dimentionless), eq. (2) & (3)	$\text{Risks' score} = 0.5 * \text{Scale up risk} + 0.25 * \text{Mass integration risk} + 0.25 * \text{Energy integration risk}$		
	Scale up risk	Judgment based, using a relative scale. E.g. relative to the most similar commercial project: 5. If numbers of different unit of operation is 2 or less than 2, the risk score is 0. 6. If it is between 2 and 10, for each number of unit more than 2, value of 0.01 should be added to 0. However numbers of different units should not be more than 11, otherwise it shows the technology is prone to have a high risk at the time of implementation.	0 to 0.09
	Mass integration risk	Judgment based, using a relative scale. E.g. if there is a linkage between a new process and a pulp process, that can potentially result in negative impact in the core business, the risk score is 0.02. However this risk is eliminated through in-situ testing.	0 or 0.02
	Energy integration risk	Judgment based, using a relative scale. E.g. relative to energy system of a targeted pulp mill: If the energy requirement of new process is equal or less than the existing energy system, the risk score is 0.	0, 0.06 or 0.12

		5. If it marginally exceeds the design capacity of the turbines or boilers, the risk score is 0.06. 6. If it significantly exceeds the design capacity of the turbines and boilers, the risk score is 0.12. However this risk is eliminated through capital expenditure.	
Optimism bias, (dimentionless), eq. (2) & (3)	Judgment based, using a relative scale. E.g. relative to how each technology developer over-value their technology, how they believe optimism bias effects cost estimates prior to commercialization, how they address this bias relative to your technology, etc.		0 to 0.08
Economies-of-scale, (%)	Fixed operating cost: case-by-case assessment		0 to 100
	Capital cost [10]: $C = C_{ref}\left(\frac{M}{M_{ref}}\right)^{\alpha}\left(\frac{i}{i_{ref}}\right)$		0 to 100
Process operation optimization due to learning, (%)	Case-by-case assessment related to cost reduction rate of the following sections: • Labor cost • Raw material cost • Maintenance cost		0 to 100
Process design optimization and less conservatism in design due to learning, (%)	Case-by-case assessment related primarily to: • Uncertainty in design parameters. • Complexity of the overall process.		0 to 100
Process improvement	Case-by-case assessment based on identified incremental new technology changes.		0 to 100

with new technology additions post-implementation, (%)		

The objectives of this study are:

- To demonstrate the application of experience curve model in cost assessment of dissimilar lignin-based biorefinery cases.
- To interpret the result of this application for biorefinery strategy decision-making.

The overall methodology of this study includes following four steps (fig. 2).

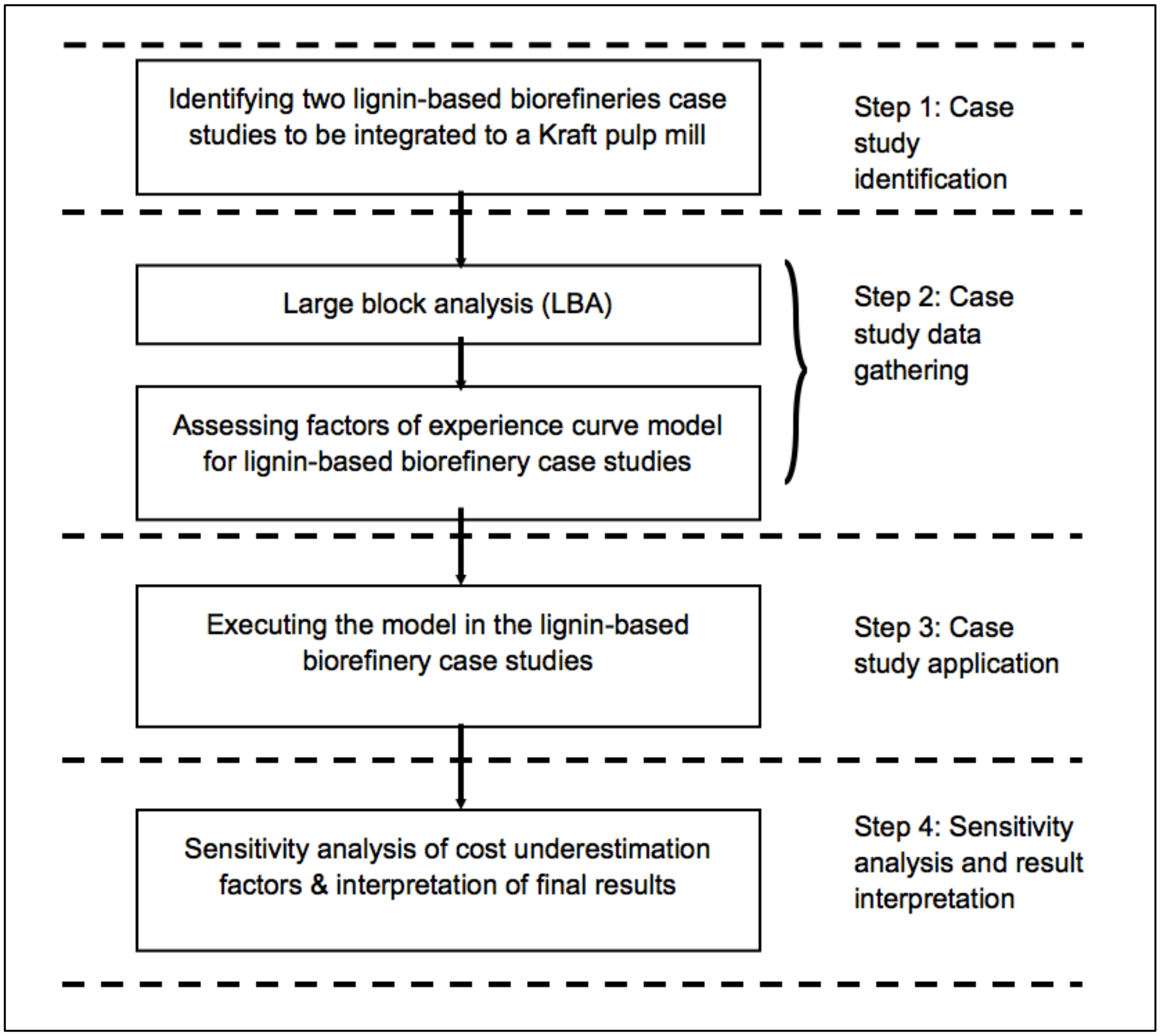


Fig. 2- Schematic representation of the methodology

The first step was to identify two emerging lignin-based biorefinery cases with two characteristics: 1- commercially unproven 2- at deferent stages of development; e.g. one in pilot and another one in demonstration scales.

In The second step, Large Block Analysis (LBA) was performed on the cases. This could bring them to an applicable level of comparison based on same assumptions. Moreover the factors of experience curve model were assessed. This assessment for the case studies can be done based on information from industry partners' interviews and models from table 1.

The third step was to execute the model by feeding the data from step 2 to the model. Finally the numerical results were interpreted.

Two different lignin-based biorefinery strategies are identified:

- Technology 1: Solvent pulping, at pilot scale

This is a standalone technology for integration into a pulp and paper mill. Wood chips are used for the production of PF resin precursor, sugar syrup, ethanol and acetic acid in this process. The process uses solvents to extract specific components (e.g. hemicellulose) from the wood.

- Technology 2: Lignin precipitation, at demonstration scale

This technology uses black liquor from the Kraft pulping process and extracts lignin by acid precipitation. The liquor is then returned to the recovery cycle, and the lignin dried and used for PF resin precursor production.

Results of LBA are shown in fig. 3 and 4 and table 2.

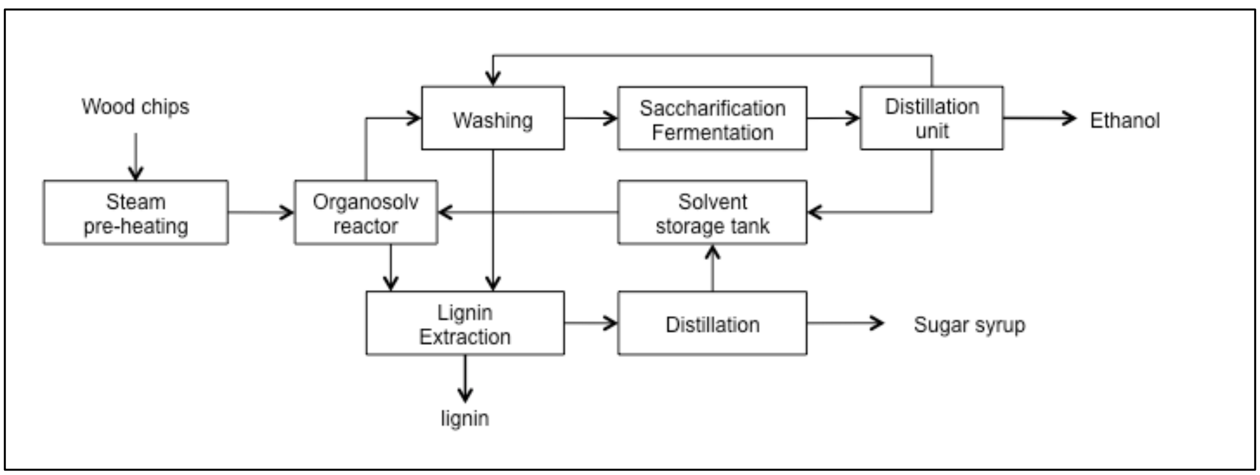


Fig. 3- Block flow diagram of solvent pulping process

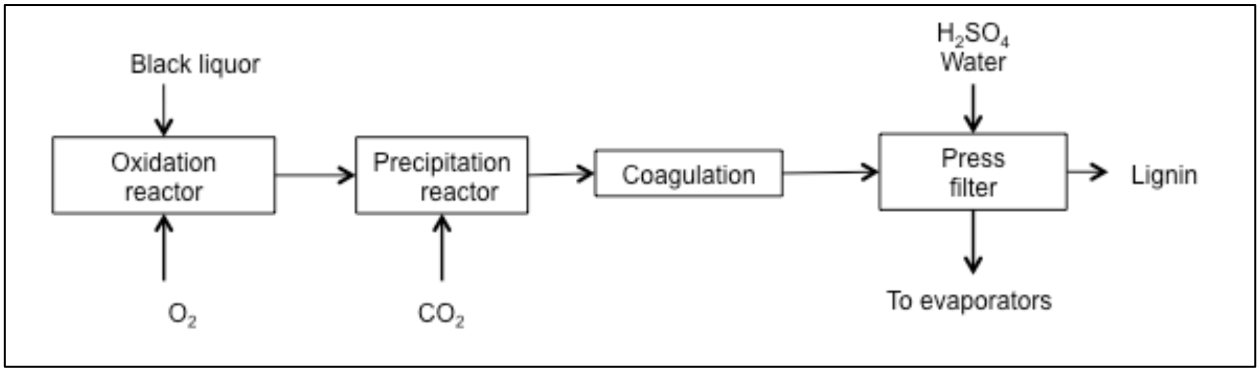


Fig. 4- Block flow diagram of lignin precipitation process

Table 2- Values for estimated annual total capital cost, annual total operating cost and annual production capacity

Variable name	Solvent pulping	Lignin precipitation
Estimated annual capital expenditure (m$/year)	36	3
Total project investment (direct capital cost), (m$/year)	19	2
Estimated annual operating cost (m$/year)	272	61
Estimated annual production capacity of total products (ton/year)	480,000 (38% PF resin precursor, 36 % sugar syrup, 23% ethanol, 3% acetic acid)	61,000 (100% PF resin precursor)
Estimated annual production capacity of PF resin precursor (ton/year)	184,000	61,000

Table 3 presents values of:

1- Cost underestimation factors (using table 1 and information from industry partners' interviews)

2- Actual total cost per ton of product for first commercial scale (using eq. 1, 2 and 3)

3- Errors in estimated costs per ton of product for first commercial scale (using eq. 4).

$$\text{Actual total cost per unit of product} = \frac{\text{Actual annual capital expenditure} + \text{Actual annual operating cost}}{\text{Estimated annual production capacity}} \quad \text{(E-1)}$$

$$\text{Actual annual capital expenditure} = \frac{\text{Estimated annual capital expenditure}}{0.5 * \text{Known technology} + 0.5 * \text{Project definition}} * \frac{1}{(1 - \text{Risks'score}) * (1 - \text{Optimism bias})} \quad \text{(E-2)}$$

$$\text{Actual annual Operating cost} = \frac{\text{Estimated annual operating cost}}{(1 - \text{Risks'score}) * (1 - \text{Optimism bias})} \quad \text{(E-3)}$$

$$\mathrm{e_P} \text{ or } \mathrm{e_D} = \text{Actual total cost per unit of product} - \frac{\text{Estimated annual capital expenditure} + \text{Estimated annual operating cost}}{\text{Estimated annual production capacity for first commercial scale}} \quad \text{(E-4)}$$

Table 3. Actual total cost and design estimated cost error per ton of PF resin precursor for first commercial scale variables

Variable name	Solvent pulping process	Ligning precipitation process

Known technology, (%), [3]	58 Comments: 79 (m$/year) investment in new technologies such as: - Saccharification unit: uncertainties about the type of vessel that has to be used in commercial scale. - Solvent recovery unit: uncertainties about the recovery of solvent. - Lignin precipitation unit: uncertainties about the techniques to achieve the targeted quality of lignin.		72 Comments: 611000 ($/year) investment in new technologies such as: - Filter press and dryer units: these technologies have never been used for lignin precipitation process at commercial scale. - Coagulation unit: this technology has never been used at commercial scale.
Project definition, (%), [3]	90 Comments: 70% of detailed engineering step is completed.		95 Comments: 80 % of detailed engineering step is completed.
Risk score, (dimensionless)	0.05		0.02
	Scale up risk	0.02 Comments: relative to the most similar commercial project, the different unit of operations are: 1- Lignin precipitation, 2- Distillation tower, 3- Evaporator, 4- Digestion vessel (in case of type vessel there are uncertainties in scale up).	0.01 Comments: relative to the most similar commercial project, the different unit of operations are: 1-Filter press, 2- Dryer, 3- Lignin coagulation.
	Mass integration risk	0.02 Comments: It is a stand-alone process so it has few impacts	0 Comments: - It will not affect the pulp

		on pulp production process such as: - Materials handling system: it has to be adapted to biomass procurement scenarios of the host pulp mill. - Waste water treatment: Uncertainties about the separation process of water and solvent, so this may affect waste water treatment of the mill.	production process. - It has no disruptive impact on waste water treatment.
	Energy integration risk	0.12 Comments: - Steam and electricity productions have to be adapted and optimized according to requirements of the both pulp and solvent pulping processes. - There is no need for a new boiler, only additional costs in using one of the power boilers and electricity consumption have to be considered.	0.06 Comments: - Lignin precipitation units are easily integrated within the existing energy system. - Additional natural gas need to be fed into one of the power boilers. - It decreases the amount of organics in the black liquor, so energy management need to be adapted.
Optimism bias, (dimensionless)	0.03		0.06
	Comments: This factor was quantified using a relative scale by several questions that were asked during the industry partners' interviews such as: describe how technology developers over-value their technology? describe how do you believe optimism bias effects cost estimates prior to commercialization? how		

	do you address this bias relative to your technology?, etc. Based on discussions during the interviews, solvent pulping technology providers seem to have less optimism bias than lignin precipitation technology providers.	
Actual total cost per ton of PF resin precursor ($/ton)	1900 Comments: Each ton of total production includes 38% PF resin precursor,36 % sugar syrup, 23% ethanol and 3% acetic acid.	1100 Comments: Each ton of total production includes 100 % PF resin precursor.
Errors in estimated costs per ton of PF resin precursor ($/ton)	200 Comments: Each ton of total production includes 38% PF resin precursor,36 % sugar syrup, 23% ethanol and 3% acetic acid.	100 Comments: Each ton of total production includes 100 % PF resin precursor.

Table 4 presents values for:

1- Cost reduction factors (using table 1 and information from industry partners' interviews)
2- Experience index (b, based on information from Cost reduction factors and eq. 5)
3- Progress ratios (PR, eq. 6)

$$b = \frac{\mathrm{Ln}\frac{C_n}{C_0}}{\mathrm{Ln}\frac{CUM_n}{CUM_0}} \qquad \text{(E-5)}$$

C_0: Total cost per unit of production for first commercial scale (using eq.1)

C_n: Total cost per unit of production for nth plant (based on effects of cost reduction factors from table 4)

CUM: Cumulative unit of production

$$\mathrm{PR} = 2^{b} \tag{E-6}$$

Table 4. Emerging biorefinery independent factors of cost reduction, progress ratio estimate at 10th cumulative production.

Variable name	Solvent pulping	Lignin precipitation
Effects of economies-of-scale on total capital cost reduction per ton of product	Around 60% reduction in capital cost per ton of PF resin production.	There is no effect of economies of scale for this process. The reason is that this process is highly resticted to black liqour production from Kraft process. Lignin precipitation process production capacity increases if the Kraft process' s capacity production increases.
Effects of economies-of-scale on fixed oprating cost reduction per ton of product	90% reduction in fixed operating cost per ton of PF resin production.	There is no effect of economies of scale for this process. The reason is that this process is highly resticted to black liqour production from Kraft process. Lignin precipitation process production capacity increases if the Kraft process' s capacity production increases.
Effects of process operation optimization	Labor costs: Around 20% reduction in operating labor cost (fewer people; from 57 to 52) per ton of PF resin production.	Labor costs: Around 60% reduction in operating labor cost (fewer people; from 7 to 3) per ton of PF resin

	This is due to improved experiences in operations and maintenance and better equipment selection. Energy costs: Around 15% reduction in energy costs. This is due to process improvements and energy efficiency. Feedstock costs: 45% and 25% reduction in enzyme and biomass costs by 2020 respectively. This is due to optimization in production yield and recycling of enzymes and optimization in harvesting and transportation of woods [12]. Maintenance cost: Around 25% reduction in maintenance cost due to learning.	production. This process is an integrated process to Kraft pulp mills so the required labors can be shared between to processes. Few persons may be needed for quality control. Energy and feedstock costs: 40% reduction in energy and chemical costs. This is due to process improvements, energy efficiency and less CO_2 consumption. Maintenance cost: Around 25% reduction in maintenance cost due to learning.
Effects of process design optimization and less conservatism	Design uncertainties could add up to 20% to equipment costs for the first plant. This cost will be reduced for the subsequent plants. The uncertainties are mostly in how certain processes will scale up and how much potential there is, for process improvement with experience.	Better integration of their process into pulp processes can result in reduction of the capital cost. However in this study this impact was not considered due to lack of available information about this improvement.
Effect of process	10% more energy saving by	100% reduction in CO_2 cost by

improvement with incremental new technology additions post-implementation	converting the process from batch to continuous process.	a replacement for acidification agent CO_2 (e.g. using H_2SO_4).
b, (dimensionless)	-0.37	-0.05
Progress ratio, (%)	77	96

In addition to above factors, there is another potential for capital cost reduction. This is related to capital cost's contingency that is considered for first commercial scale. This will not be considered for capital cost per ton of product after first commercial scale. Therefore there are some reductions in capital cost right after first commercial scale. According to results of industry partners'' interview this contingency for solvent pulping process is around 15% and for lignin precipitation process is around 20%. Figures 5 and 6 exhibit experience curves of solvent pulping and lignin precipitation processes. At right side of these graphs total cost per unit of product is calculated using following equation:

$$C_n = C_0 * \left(\frac{CUM_n}{CUM_0}\right)^b \qquad \text{(E-6)}$$

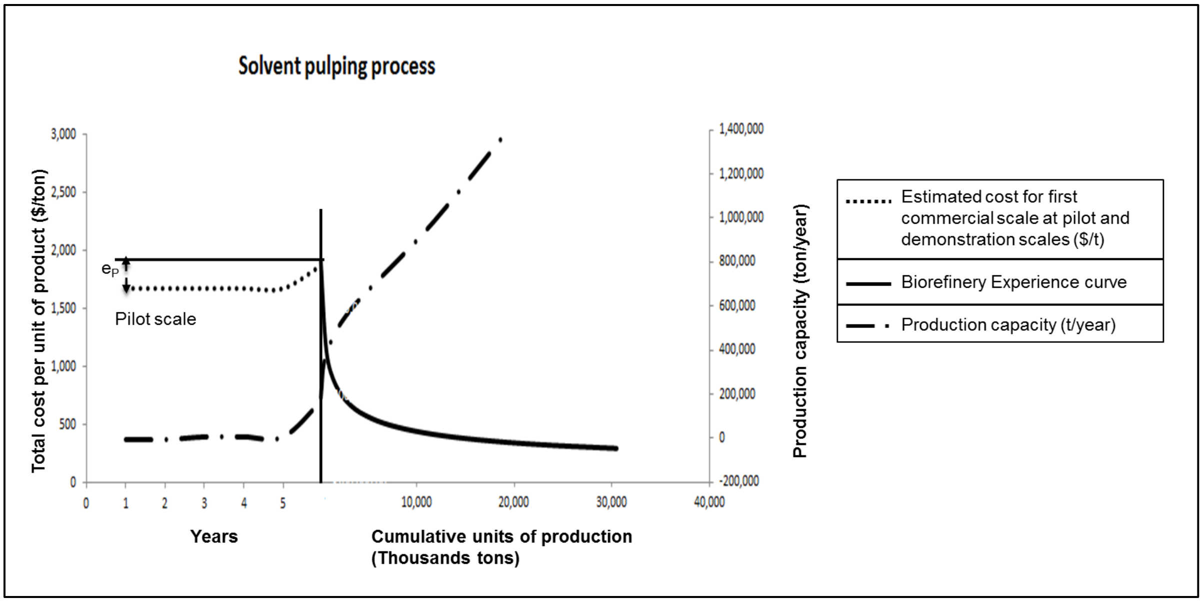


Fig. 5- Solvent pulping process experience curve

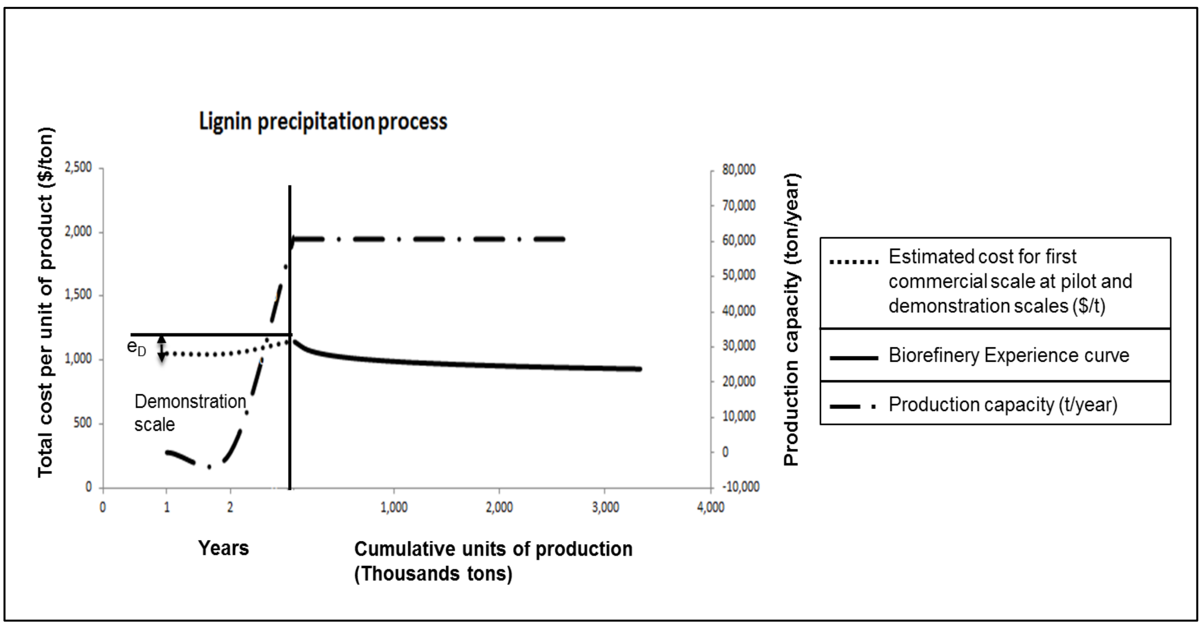


Fig. 6-Lignin precipitation process experience curve

Figures 5 and 6 show cost overruns of each case study at first commercial scale and experience curve at post commercial scale. The actual total cost per ton of PF resin precursor for first commercial scales are: 1900 ($/ton) for solvent pulping process and 1100 ($/ton) for lignin precipitation process. This indicates that the solvent pulping process in compare to lignin precipitation process is more cost intensive. Moreover, it has more cost overrun in first commercial scale which is due to some factors such as: lower stage of development (pilot scale), more new technology and associated risks and less level of project definition. It is important to note that, for solvent pulping process PF resin precursor production is only 38 % of each ton of total production. On that account its actual total cost for each ton of total products would be 700 ($/ton, (38% PF resin precursor, 36 % sugar syrup, 23% ethanol, 3% acetic acid)).

The information from left sides of these figures can be used in business planning. For example in a short-term vision of a business strategy, lignin precipitation seems more promising. This is due to less total cost per ton of product for first commercial scale. In long term vision when market and demand of lignin products are more developed, solvent pulping process is more beneficial. This is due to three factors: 1- more potentials for future cost reduction (progress ratio of 77%), 2- more quantity and 3- better quality of lignin.

In this work, the application of experience curve model that was proposed in part one of this paper was presented. This study aimed to illustrate and interpret application of this model for lignin-based biorefineries. First a LBA on two identified lignin-based biorefinery cases was performed. Then factors of experience curve model were assessed for the case studies using results of industry partners' interviews and table 1. This information was assembled to run the model. Finally final results were interpreted.

Results showed more cost overruns in solvent pulping process (200 $ per ton of PF resin precursor) than lignin precipitation process (100 $ per ton of PF resin precursor). This is due to several factors such as:

- Solvent pulping's lower scale of development (pilot scale)
- More percentage of new technology
- Less project definition
- More associated risk score

In commercial scale, factors of cost reduction resulted in progress ratio of 77% for solvent pulping process and progress ratio of 96% for lignin precipitation. Finally, this model can provide forest product companies with useful information that can be used in evaluating and decision making of emerging biorefinery strategies. However, one has to define suitable criteria for decision-making processes such as Multi Criteria Decision Making (MCDM) to achieve such information.